MEASURING NOISE LEVEL REDUCTION USING AN ARTIFICIAL NOISE SOURCE

A Thesis
Presented to
The Academic Faculty

by

Rene Jean Robert

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Mechanical Engineering in the
George W. Woodruff School of Mechanical Engineering

Georgia Institute of Technology
December 2015

Copyright © 2015 by Rene Robert

MEASURING NOISE LEVEL REDUCTION USING AN ARTIFICIAL NOISE SOURCE

Approved by:

Dr. Kenneth A Cunefare, Advisor
Woodruff School of Mechanical Engineering
Georgia Institute of Technology

Dr. Erica Ryherd
Durham School of Architectural Engineering and Construction
University of Nebraska – Lincoln

Dr. Javier Irizarry
School of Building Construction
Georgia Institute of Technology

Date Approved: 2 December 2015

ACKNOWLEDGEMENTS

I will take this opportunity to acknowledge everyone that has helped me complete this work. I would like to thank my mom and dad, Monique and Jean Robért, for supporting me and continually pushing me. I would also like to thank my sisters, Maddie and Celeste, for always being there for me. Next, I would like to especially thank Dr. Kenneth Cunefare for offering me this opportunity for funded research as a Masters student at Georgia Tech in addition to sparking my interest in acoustics and guiding me as a student. I would also like to thank Dr. Erica Ryherd for all of the work in helping me with the project from being our point of contact, preparing monthly and annual reports, and to organizing our project meetings. Next, I would like to thank Dr. Javier Irizarry for all of his help in constructing and deconstructing the test house, as well as providing me with volunteers to help out with my testing. I would also like to thank my labmates and officemates for helping me overcome all of the obstacles that I faced along the way, especially Elliott Gruber and Ryan Salmon. Lastly, I want to thank everyone that had volunteered to help out in the construction, testing, and deconstruction of the test house, with a special thanks to David Cavanaugh and Michael Clark.

Thanks to ASCENT for providing funding for my research. Opinions findings, conclusions, and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of ASCENT sponsor organizations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

ACRP	Airport Cooperative Research Program
AI	Adjusted Indoor Level
AIP	Airport Improvement Program
AOITL	Apparent Outdoor-Indoor Transmission Loss
AS	Aircraft Noise Spectrum
ASTM	American Society for Testing and Materials
ATL	Hartsfield-Jackson Atlanta International Airport
A_2	Absorption of Receiving Room
BTV	Burlington International Airport
CCNLR	Cosine Corrected Noise Level Reduction
DoE	Department of Energy
DNL	Day-Night Average Sound Level
dB	Decibel
dBA	A-Weighted Decibel
FAA	Federal Aviation Administration
f_s	Schroeder Frequency
Hz	Hertz
IBANA	Insulating Buildings Against Aircraft Noise
ISO	International Standards Organization
L&B	Landrum & Brown

L_{ext}	Exterior Sound Level
L_{in}	Interior Sound Level
L_p	Sound Pressure Level
NEM	Noise Exposure Map
NLR	Noise Level Reduction
NR	Noise Reduction
OINR	Outdoor-Indoor Noise Reduction
OITL	Outdoor-Indoor Transmission Loss
OITC	Outdoor-Indoor Transmission Class
PGL	Program Guidance Letter
RSIP	Residential Sound Insulation Programs
RTA	Real-Time Analyzer
RT_{60}	Reverberation Time
S	Total Surface Area of Partition or Specimen
SEL	Sound Exposure Level
SLM	Sound Level Meter
SSA	Sound Spectrum Analyzer
STC	Sound Transmission Class
TL	Transmission Loss
824	Larson Davis 824 Sound Level Meter
V	Volume of Receiving Room

SUMMARY

Buildings located near airports may be subjected to significant noise levels due to aircraft flyovers. Aircraft noise is particularly annoying when compared to other traffic noises due to its intermittent nature. While noise control is typically performed at the source, sound insulation programs are in place to improve the acoustic performance of a residence affected by the flyovers. Noise Level Reduction (NLR) is a common metric used in the United States to determine whether a residence qualifies for such programs. Sound insulation programs are available to houses that have an indoor Day Night Average Sound Level (DNL) greater than 45 dBA. NLR is a single-number metric used to quantify the ability for a building or building element to reduce the transmission of external sound pressure levels generated by aircraft. In addition to determining whether a residence qualifies, NLR can be used to quantify the effectiveness of the modifications performed as a result of the sound insulation program. NLR measurements with a loudspeaker offer an alternative method to those performed with aircraft flyovers, offering flexibility to the consultants that perform these measurements in the field. The purpose of this research was to better understand and improve the loudspeaker test for measuring NLR, providing a resource to the aircraft noise industry. Testing was completed on a "test house" that was constructed on campus with construction methods typical of a mixed-humid climate. The angular dependency, repeatability, and reproducibility of NLR, among other factors, were evaluated with field measurements. Significant NLR variations were observed with changes in lateral and vertical angles of incidence.

CHAPTER 1

INTRODUCTION TO AIRCRAFT NOISE

The effect of aircraft noise on the surrounding community is a concern of both residents in affected buildings and airport operators. With the increase in air traffic over recent years, airports have expanded in both physical size and air traffic capacity causing more buildings to be affected by aircraft noise. Aircraft noise can have a significant effect on people including task interference, aversive effects on emotion and tranquility, speech interference, sleep disturbance, impairment of classroom learning, and some non-auditory health effects [1]. The impact of noise remains an obstacle to the growth of airports, restricting activity and flight paths. Studies are underway examining the effect that aircraft noise has on the community [2, 3].

Aircraft noise is seen as a particularly annoying noise source since it is a time varying, random source projected across all frequencies. Automobile traffic is a more consistent noise source, as such a person is less likely to respond to the "background noise" compared to the irregular aircraft noise sources [4]. The random nature of aircraft noise seems to be especially problematic with phone, television, or conversation interference in residences near airports [4]. Additionally, aircraft noises have an intricate frequency spectrum with energy in both the low and high ranges resulting in complications trying to mitigate both in construction.

The approach to managing aircraft noise followed traditional noise control methods by attempting to mitigate noise at the source, path, and receiver. Initially, work was done to mitigate the sound created by aircraft engines. This endeavor was successful; however, the results were largely mitigated due to increases in air traffic over time. It has been difficult to further reduce the sound generated by aircraft, thus measures are now also taken in sound insulation programs to improve the noise reduction of homes. In addition to residences, buildings such as hospitals, schools, or places of worship may also be eligible for sound insulation programs.

Eligibility for sound insulation programs provided by the Program Guidance Letter (PGL) 12-09 is broken into two steps: buildings within a 65dBA Day-Night Average Sound Level (DNL) contour and with an interior DNL of at least 45 dBA [5]. DNL is a metric used to identify noise levels of certain zones determined by the average sound level of a 24 hour period representative of a typical day in a year with a 10 dB penalty from 10:00 PM to 7:00 AM. Airports may have an associated Noise Exposure Map (NEM) depicting the DNL noise contours in 5 dBA increments for various areas around it often ranging from 65 dBA to 75+ dBA. Residences within the 65 dBA DNL contours may be eligible for modifications as part of sound insulation programs, with the extent of the modification being determined by its location within a noise contour and the transmission loss properties of the house. Government regulation performed by the Federal Aviation Administration (FAA) use a single number metric, Noise Level Reduction (NLR), to quantify the effectiveness of a building reducing exterior sound and calculate the interior DNL.

1.1 Receivers near Airports

Receivers in the source-path-receiver approach of noise control are those affected by the sound. In the case of aircraft noise, the receiver can be considered inhabitants of structures exposed to aircraft noise. In order to determine how receivers are affected by aircraft noise, it is important to first analyze the path that the sound is taking to reach the receiver. Aircraft flyovers are a line source; therefore, the path to a building from an aircraft is often unobstructed for a portion of a flyover. The path that sound is transmitted through a building to a receiver is either through a structure or an air path. Figure 1.1 demonstrates the possible paths that a sound wave will travel through a brick wall. Sound pressure waves from the aircraft will impact the structure, causing a vibration, which then radiates the wave to the receiver within the building. The other type of path that sound travels to the inside of a building is called a flanking path. Flanking paths take a variety of forms, but can be simplified as a crack or opening in the structure. High frequency sounds tend to travel better in this manner, while low frequency sounds travel better through structures [4].

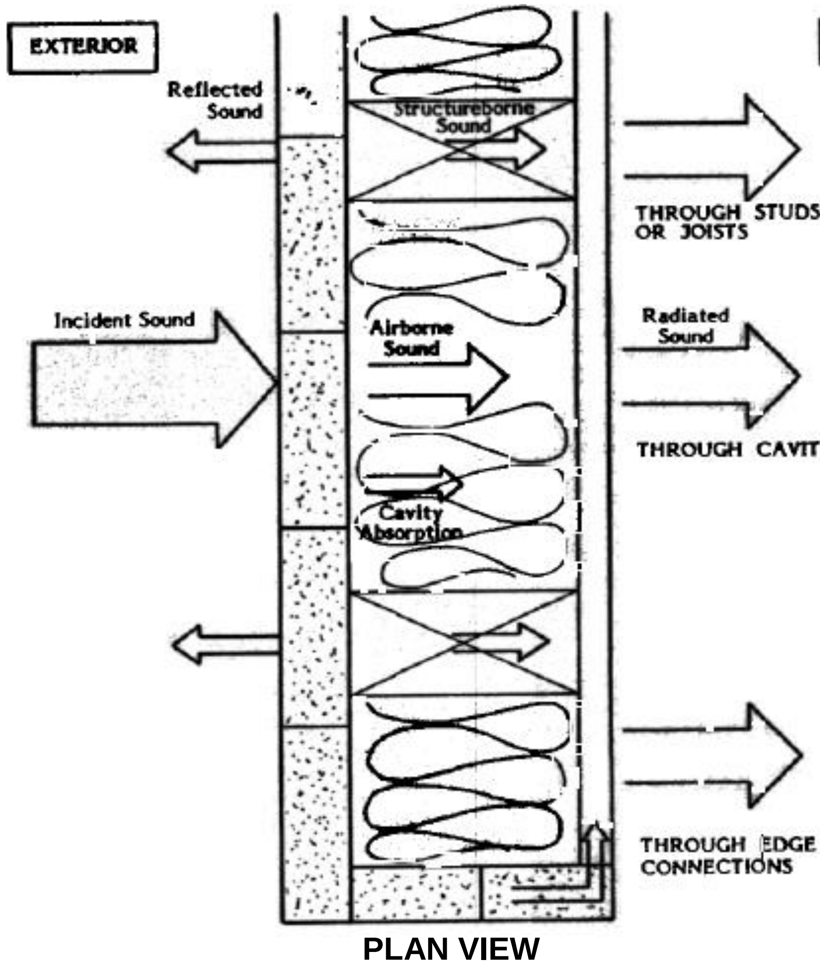


Figure 1.1: Demonstration of possible sound paths inside a building reproduced from [4]

It is important to consider both paths when attempting to mitigate sound at the receiver. A building's effectiveness at transmission loss (TL) is largely dependent on its weakest part. Thus, a wall that has a high TL performance does not necessarily correlate to a high NLR unless any possible flanking paths were addressed as well. For example, an opening of 1% on a 9' x 10' wall will reduce the TL from 40 dB to almost 20 dB [6]. This example demonstrates the necessity of treating flanking paths for a building when trying to improve its NLR. Once the flanking paths are treated, windows typically become the controlling member of the building's performance [4].

Another factor that affects the receiver is the climate of the building. The Department of Energy (DoE) divides North America into eight different regions corresponding to various climates in its "Guide to Determining Climate Regions by County": Hot Humid, Mixed-Humid, Hot-Dry, Mixed-Dry, Cold, Very Cold, Subarctic, and Marine [7]. Figure 1.2 is a map of the United States depicting seven of the eight climate regions. The subarctic is not depicted in the map, since the map only contains the mainland United States and Alaska is the only state that contains the subarctic climate. Different climates offer varying norms of construction that is better suited for its region. The DoE has also published a report titled "Introduction to Building Systems Performance: Houses That Work II" which provides best practices for constructions in each of the climates [8]. The climate and type of construction can affect the acoustic performance in various ways, with the exterior layer of sheathing having the greatest impact on the overall acoustic performance [9]. Another change in acoustical performance is due to the weatherstripping and sealing often found in colder climates [4]. The extra care taken in thermally sealing buildings has the added benefit of reducing flanking paths into the building. Additionally, colder climates tend to have heavier roofs to withstand the weight of snow as well as thicker windows and doors to help provide thermal insulation to the building. Thermal insulation does not always correlate well with acoustic insulation, but typically at least provide minimal benefits.

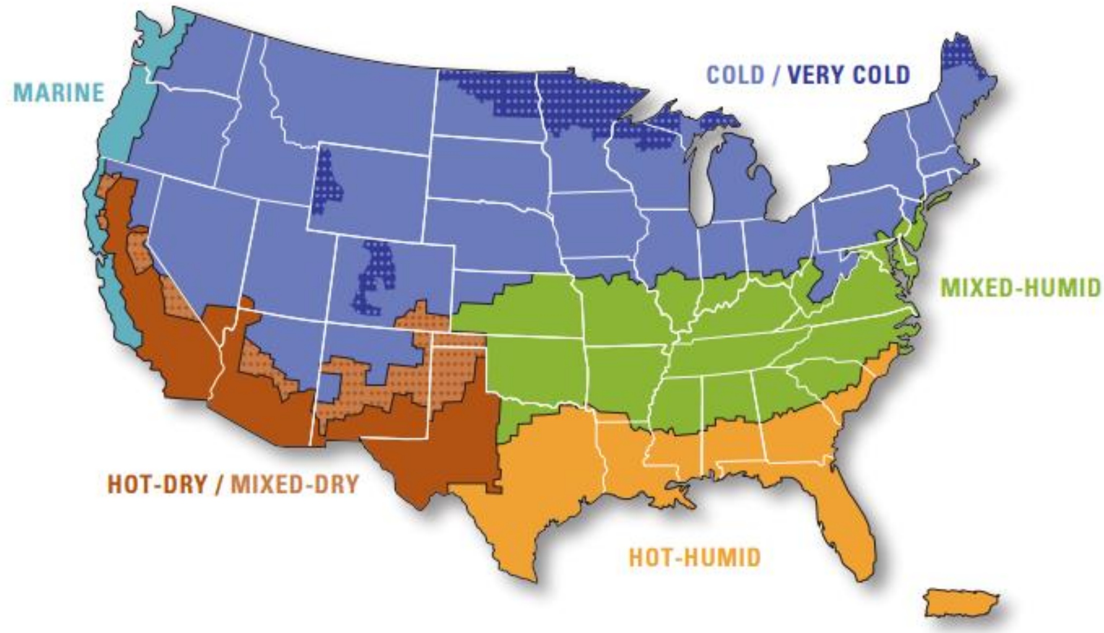


Figure 1.2: Map of the climate regions in the United States reproduced from [7]

1.2 Sound Insulation Program

Aircraft noise is one of the most important environmental concerns of airport operators. In a survey completed by the United States General Accounting Office in 2000 on the fifty busiest commercial airports in the United States, noise issues were selected as a major concern by thirty-three of the airports, which was the most when compared to other environmental issues [10]. Once notice was taken to look at buildings near airports, a number of sound insulation programs have been developed over the years. The first airport-sponsored sound insulation program was proposed at the Los Angeles International Airport in 1967 [11].

One of the first documents endorsed by the FAA that detailed sound insulation programs is the "Guidelines for the Sound Insulation of Residences Exposed to Aircraft Operations," when it was released to the public as part of an advisory circular by the FAA in 1992 [4]. This report was created to provide guidelines for sound insulation programs including studying, initiating, and implementing these programs for residences near airports. Since this report, Wyle Laboratories has published a second version in 2005 with the same title to update some of the guidelines [11]. Some of the updates include new cost values, room-by-room recommendations for existing homes, and whole-house recommendations for new construction. In addition to studies looking at construction of houses near airports, the effect of aircraft noise on public buildings such as school and hospitals were also examined by the FAA [12, 13]. Lastly, the Airport Cooperative Research Program (ACRP) published an extensive update in 2013 titled "Guidelines for Sound Insulation Programs" [14].

The PGL 12-09 determines whether or not a residence qualifies for the sound insulation program [5]. Eligibility is determined by two main factors: whether the residence is located within the 65 dBA DNL noise contour and the interior DNL is greater than 45 dBA. The NEM containing the noise contours for the airport must have been created within the last five years to be used as a reference. A building satisfying these requirements may be eligible to receive funding as part of the Airport Improvement Plan (AIP) as is listed in the AIP Handbook [15]. If a building does qualify, modifications are performed such that the interior DNL is less than 45 dBA. The program also specifies that there must be a change of at least 5 dB in the NLR of the building if any modifications are performed. A change in sound level of 5 dB is the minimum change in sound level that a typical person will perceive.

As mentioned previously, aircraft flyovers are a complicated sound source with energy across a range of frequencies. It is important to understand that some building construction is better at attenuating noise in certain frequencies than others. For example, the performance of a structure at mid-to-higher frequencies is controlled by the mass of the structure. On the other hand, resilient structures are usually more effective at attenuating noise in the lower frequencies [16]. An ideal wall is heavy, but not stiff to be effective across all frequencies; however, such walls do not exist [17]. Double walls may be used to add mass for the mid-to-higher frequencies or vibration isolation techniques may be used to improve the acoustic performance at lower frequencies.

In addition to sound insulation programs, ordinances may be in place to provide construction requirements to meet a certain NLR value. A common practice in some ordinances is to provide Sound Transmission Class (STC) requirements in order to satisfy a general NLR condition. For example, Pima County, AZ requires STC 47 walls and STC 28 windows in construction of a building with a minimum NLR requirement of 25 dB [18]. The NLR was calculated for an 8'x10' wall with a 3'x5' window using the transmission loss associated with the composite wall using the STC requirements. The example wall resulted with an average NLR of 21.4 dB, resulting in a lower NLR than the requirements. While this type of ordinance is helpful, they should not be blindly implemented assuming that the construction will satisfy the NLR condition. Flanking paths should always be considered in construction since even a small opening will have a great impact on the performance of a structure. Also, STC values are weighted to be used with speech spectra rather than aircraft spectra. Standard ASTM E1332-10a specifically states that Outdoor-Indoor Transmission Class (OITC), discussed in section 2.6, is a better metric for construction affected by aircraft spectra and should be used in such circumstances [19]. Additionally, high STC ratings do not always correlate to high performance against low frequency noises since STC ratings are better used in a speech setting where low frequency noises are not the primary concern. Aircraft spectra will often contain a significant amount of low frequency noise that needs to be treated as part of sound insulation programs. Thus, there is a chance that higher STC ratings will not translate to good acoustic performance with low frequency sounds.

1.3 Previous Aircraft NLR Studies

1.3.1 Comparison of Tests of NLR Measurements in the Field

Landrum and Brown (L&B) performed a series of tests as part of a study at the Burlington International Airport (BTV) to study variation in NLR measurements [20]. The study specifically focused on two tests: the loudspeaker test as presented in ASTM E966-10 and the aircraft flyover test described in the FAA's 1992 circular [21]. Both methods were used to measure NLR in six houses and eleven rooms near BTV. L&B determined the aircraft flyover test measurements had mean NLR values 2.4 dB greater than the loudspeaker test. The report also included comparisons to different factors within each method. The overall variation in NLR measurements was broken down into three major components: human variation such as data acquisition and measurement setup, measurement method such as microphone placement and noise source height, and analysis method specifically in regards to the aircraft spectrum used in calculation.

1.3.2 Comparison of NLR Lab Measurements to Simulated Results

Another study was completed by Thomas to compare measurements performed in a laboratory setting to simulated results [22]. The test house was constructed in a hemi-anechoic chamber with methods and practices of construction typical of a mixed humid climate. The overall goal of the study was to evaluate and offer improvements to modeling software in predicting NLR. Ideally, improved models will allow for better predictions of construction performance before and after modifications as part of a sound insulation program. Thomas determined that the main difference in results was caused by the modeling software not including certain testing parameters such as angle of incidence.

CHAPTER 2 TERMINOLOGY

There are various terms to quantify sound; however, the sound pressure level presented in decibels (dB) or A-weighted decibels (dBA) is the most general form. Sound pressure levels provide a logarithmic value for the energy contained in a specified frequency or range of frequencies. Pure tones or similar sounds may only contain energy in certain frequencies; but intricate sounds, such as aircraft noise contain energy across various frequencies. Thus, metrics are available for use when dealing specifically with aircraft noise. Additional metrics are available to analyze differences in levels between two sound fields separated by a barrier. The following metrics are the most prevalent ones used in relation to aircraft noise and the Federal Aviation Administration (FAA).

2.1 Noise Reduction

The noise reduction (NR) of a building or building element is the difference in sound pressures on each side of the barrier across a range of frequencies, typically presented as a dB value for frequency bands. A free-field exterior measurement records the exterior sound pressure levels while a diffuse sound field interior measurement records the interior sound pressure levels [23]. An interior diffuse sound field is measured by taking an average of several fixed locations or sweeping the microphone throughout the space. Either of these methods reduces the effect that averse room acoustics, such as standing waves, have on the measurement. The NR values are calculated by subtracting the interior sound levels and a correction factor from the exterior sound levels. The correction factor depends on the method used to collect the data and will be discussed in section 3.3. Figure 2.1 depicts example NR values for a measurement presented as a value for each one-third octave band frequency.

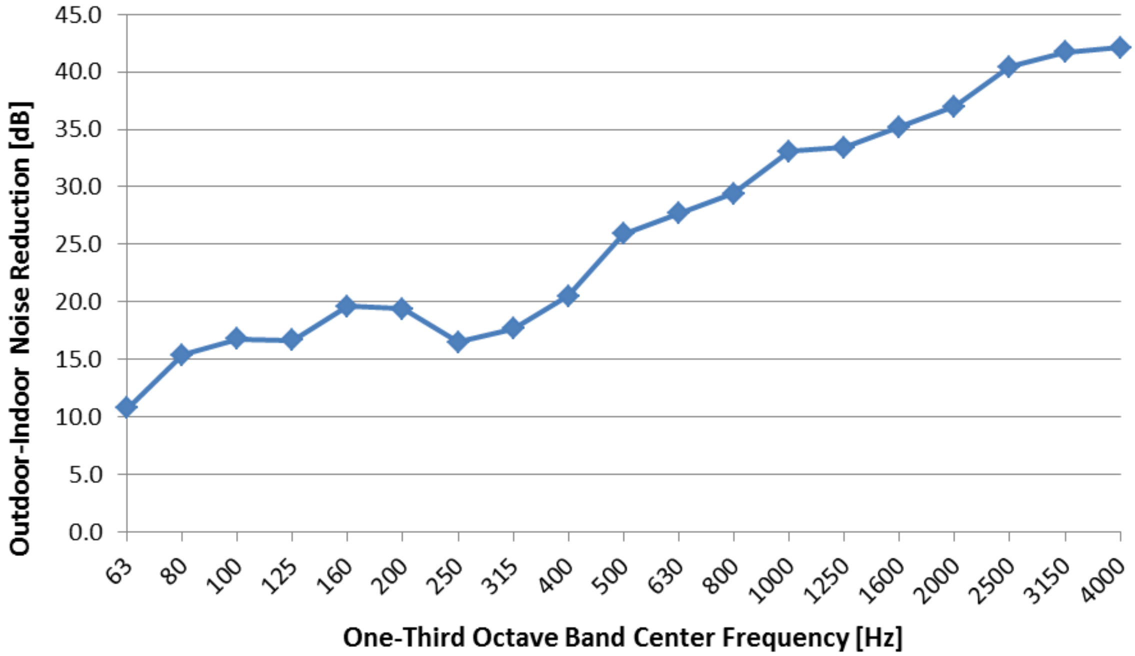


Figure 2.1: NR for an example measurement

NR is equivalent to Outdoor-Indoor Noise Reduction (OINR) as defined in ASTM E966-10; however, OINR is more focused on a façade or façade element rather than the performance of the whole building [21, 24]. The standard provides six different methods to measure OINR: three of the methods require the actual traffic source (aircraft flyovers) as the sound source, two require a loudspeaker, and the last requires a calibrated loudspeaker. Table 2.1 provides a summary table of the different methods within ASTM E966-10 as well as the source and application suggestions for each. It is important to note that the second measurement method, fixed near, states it should be used when the third method, fixed flush, is not possible.

Table 2.1: List of methods reproduced from ASTM E966-10 [21]

	Outdoor Signal Source Loudspeaker Required for OITL or AOITL	Outdoor Microphone Position	Applications Remarks
1	Calibrated loudspeaker	Incident sound pressure inferred from separate calibration of source	Use when outdoor measurement at or near specimen is not possible
2	Loudspeaker	Several locations averaged about 1.2 m to 2.4 m from the façade element	Use when calibrated source or flush measurement is not possible
3	Loudspeaker	Several locations less than 17 mm from specimen	Use when the loudspeaker cannot be calibrated
4	Traffic, aircraft, or similar line source	Simultaneous measurement remote from the specimen	Use when it is possible to measure source in free field at same distance as specimen.
5	Traffic, aircraft, or similar line source	Simultaneous measurement 2 m from the specimen surface	Use when remote measurement or flush measurement is not possible.
6	Traffic, aircraft, or similar line source	Simultaneous measurement with entire microphone diaphragm within 17mm of the specimen	Use when remote measurement is not possible.

Laboratory measurements for NR performed in a reverberation room are outlined in ASTM E596 – 96, but the lab values are not definitive of the acoustic performance of a structure in actual construction [25]. Measurements must be taken of the constructed structure in the field to determine the NR of the structure.

2.2 Transmission Loss

Transmission loss (TL) is a metric used to quantify the transmission of sound through a barrier. It is equivalent to Apparent Outdoor-Indoor Transmission Loss (AOITL) in ASTM E966-10, although AOITL is dependent on the angle of incidence, θ [21]. It is also similar to Outdoor-Indoor Transmission Loss (OITL); however, the OITL metric may only be reported if no significant flanking paths were identified in the structure through testing. OITL and AOITL are properties of a façade or façade element measured in the field. Their values are determined by applying measured NR data to

$$\mathrm{OITL}(\theta) = \mathrm{OINR}(\theta) + 10 * \log\left(S * \cos(\theta) / A_2\right) + 6 \text{ [dB] [21].} \quad (2.1)$$

The same equation can be used to calculate AOITL instead of OITL if there were no flanking paths in the structure. OINR (θ) is the NR data measured using the procedure listed previously for a specific angle of incidence, θ. S is the area of the test subject such as a facade, and A_2 is the absorption of the room calculated with the volume of the receiving room, V, defined by

$$A_2 = V^{2/3} \text{ [m}^2\text{] [21].} \quad (2.2)$$

A laboratory method for measuring the TL in two adjacent reverberation rooms is outlined in ASTM E90-09 [26]. This procedure is usually implemented in determining the transmission characteristics of a building partition. The transmission loss data from this method can be used in calculating the Sound Transmission Class, and is often used to characterize construction elements such as composite walls.

2.3 Sound Transmission Class

Sound Transmission Class (STC) is a single number rating for measurements of sound attenuation for a building element and can be measured in either a laboratory or field setting in accordance with ASTM E413-10 [27]. STC is used as a metric to compare the acoustic performance of construction materials, specifically in regards to its performance dealing with speech or similar sources. Therefore, it is better suited for interior constructions such as offices or a shared partition in a residential building rather than for external walls. The STC of a structure is evaluated by determining the curve fit of the contour presented in Table 2.2 to TL data of the structure. The STC rating is defined by the reference contour for which the sum of the deficiencies is less than or equal to 32 dB and the maximum deficiency is less than 8 dB, where a deficiency is a frequency band value for which the TL data is less than the reference contour [27].

Table 2.2: Reference contour for calculating STC reproduced from [27]

Frequency, Hz	125	160	200	250	315	400	500	630
Value, dB	−16	−13	−10	−7	−4	−1	0	1
Frequency, Hz	800	1000	1250	1600	2000	2500	3150	4000
Value, dB	2	3	4	4	4	4	4	4

2.4 Noise Level Reduction

Noise Level Reduction (NLR) is the difference in the overall sound pressure levels outside and inside of a building exposed to aircraft flyover noise quantified as a single number. NLR can also be considered as the difference between the Day-Night Average Sound Level (DNL, discussed in section 2.5) outside of the structure and the DNL inside the structure [24]. It is a common metric used in the United States to determine whether a residence qualifies for sound insulation programs as well as the effectiveness of modifications completed as part of the program. Policies will specify the maximum DNL for the inside of a building; thus, based on the exterior DNL a required NLR for a building is determined to achieve this condition.

ASTM E966-10 outlines the procedure to measure Outdoor-Indoor Noise Isolation Class (OINIC), which is a similar but not equal metric [21]. The main differences between NLR and OINIC is that NLR is a spectrum dependent metric, dealing specifically with aircraft spectra. The aircraft spectra should be a sample of the typical fleet of aircraft for which the building is exposed over the course of the year. As such, NLR is dependent specifically to its location [24]. NLR and OINIC are calculated by taking the logarithmic sum of the NR values of a building or building element which was measured with the procedures discussed in section 2.1. Both the traffic sound source of aircraft flyovers and the loudspeaker tests are permitted in measuring NLR, but extra steps must be taken in calculating NLR when a loudspeaker is used. Dr. Hua He provides a method to bridge the gap between the standard and the resulting NLR values presented by consultants in "Aviation Noise Transmission Indoors – Overview of FAA Research and Assessment of Future Research Notes" [24]. The method he provides was used to determine the NLR calculation steps in 2.4.1.

ASTM E966-10 states that the FAA is flexible in allowing both the loudspeaker and flyover tests for measuring NLR, but currently recommends the aircraft flyover test [21]. The Program Guidance Letter (PGL) 12-09 states that an airport sponsor should use the 1992 guidance provided by the FAA in determining whether an airport qualifies for the Airport Improvement Plan [5]. The 1992 guidance contains no references to the artificial noise source test [4]. The Airport Improvement Program Handbook published by the FAA offers a similar statement in regards to determining the interior DNL by procedures listed in the 1992 guidance [15]. ACRP Report 89 provides the following statement regarding the issue: "Sponsors are advised to consult with their local (Airport District Offices) for direction on allowable means and methods of testing" [23]. Although both methods of measuring NLR are prevalent in the field, there is no mention of the loudspeaker tests in FAA policy. It is important to check viability of each test for a given location before selecting which test to use.

In addition to uncertainty in the viability of both methods, little guidance is offered by the FAA for measuring and calculating NLR. Most consultants cite a combination of ASTM E966 or document such as ACRP Report 89, but there is no mention of either of these documents by the FAA in the PGL 12-09 [5, 21, 23]. Specific steps in calculating NLR are often not listed such as how the frequency spectrum is selected, specifically for the loudspeaker test. Additionally, there are no requirements as to the frequency bands to be used in calculation of NLR. ASTM E966-10 states that the measurements should be conducted in one-third octave bands from at least 80-4000 Hz and preferably to 5000 Hz [21]. Another standard often cited in the calculation of NLR, ASTM E1332-10a, also uses the one-third frequency bands from 80-4000 Hz in its calculation of Outdoor-Indoor Transmission Class [19]. ASTM E413-10 uses one-third octave frequency bands from 125-4000 Hz in its calculations [27]. The procedure to measure the transmission loss of a structure in ASTM E90-09 states that the minimum frequency range used should be from 80-5000 Hz [26]. Thomas used the 50 to 5000 Hz one-third octave band frequencies when comparing the modeled NLR to the measured NLR [22]. Lastly, consultants at Landrum & Brown used full octave band frequencies from 63-4000 Hz [20]. It is unclear as to what effect the selection of the frequency bands or frequency spectrum has on the NLR calculations.

2.4.1 Artificial Noise Source Test

The initial measurements of NLR required methods using aircraft flyovers, as was performed in the testing of schools, hospitals, and public health facilities near airports in 1977 [12]. Nevertheless, this is no longer the case as loudspeakers are frequently used by acoustic consultants due to their increased flexibility and less time consuming measurements when compared to flyover tests. Loudspeakers are typically mounted on a boom and elevated at a location that approximates angles from an aircraft flyover or simply mounted on a tripod [23].

Extra steps must be taken in calculating NLR when measurements are performed with the loudspeaker test [24]. The NR of a building or building element is measured using a pink noise spectrum played over the speaker. A representative aircraft noise spectrum (*AS*), based on the typical sample of aircraft characteristic of the area, is needed to generate the NLR from the building's NR. For all of the measurements presented in this study, the aircraft spectrum in Table 2.3 provided by IBANA-Calc was used [28]. To apply the aircraft spectrum, the NR is subtracted from the *AS* in order to obtain adjusted indoor levels (*AI*) across the frequency band,

$$AI = AS - \mathrm{NR}\ \text{[dB]}. \tag{2.3}$$

The logarithmic sum of the *AI* across the one-third octave frequency band is subtracted from the logarithmic sum of the *AS* across the one-third octave frequency band to obtain the NLR,

$$\mathrm{NLR} = 10\log\left(\sum_i 10^{AS_i/10}\right) - 10\log\left(\sum_i 10^{AI_i/10}\right)\ \text{[dB]}. \tag{2.4}$$

This procedure is similar to the method for calculating the Outdoor-Indoor Transmission Class as outlined in ASTM E1332-10a [19].

Table 2.3: Standard jet aircraft source spectrum reproduced from [28]

One-third Octave Band Frequency [Hz]	Sound Pressure Level [dB]
63	104.2
80	105.7
100	107
125	107.4
160	107.1
200	106.7
250	105.6
315	104.6
400	103.9
500	103.3
630	102.8
800	101.8
1000	100.6
1250	99.3
1600	97.7
2000	95.6
2500	93.7
3150	91.5
4000	88.3

2.4.2 Aircraft Flyover Test

Aircraft flyovers provide a number of unique characteristics as a sound source that distinguishes it from the loudspeaker. Aircraft flyovers are a time-varying line source; the sound levels fluctuate depending on the aircraft path. Consultants performing measurements must take multiple measurements for each façade to ensure that an adequate sample of the paths and type of aircraft representative of the area are present. Although this information may hinder the ease of testing, the type of aircraft and common flight paths are helpful resources that may be used in analysis.

ASTM E966-10 provides three methods for measuring NR using a traffic source, aircraft flyover, but states that these methods should only be used to measure OINR not OITL [21]. Measurements require measuring the average sound pressure level of an aircraft flyover for the duration of the event, to obtain the sound exposure level (SEL) of the flight. Therefore, indoor and outdoor measurements must be taken over the same time interval simultaneously. NLR is then calculated by taking the logarithmic sum of the measured NR values, calculated as the difference between the indoor and outdoor SELs.

2.4.3 Comparison of Tests

Although both sources, speakers and aircraft, are acceptable for NLR measurements, there are a number of characteristic differences between the types of sources. An aircraft flyover is a line source that varies over time and provides free-field coverage of a structure. The artificial noise source test, or loudspeaker test, consists of a static point source. Regardless of the differences, there are benefits and drawbacks to each of the tests. Table 2.4 from ACRP Report 89 provides an overall summary comparing the two tests [23].

Table 2.4: Comparison between two tests of measuring NLR reproduced from [23]

	Flyover	**Artificial Noise Source**
Diffuse sound source	Yes	Marginal
Repeatable measurement	No	Yes
Adverse room acoustic effects	Yes	Minimal
Statistical results	Yes	No
Elimination of bad results	Some	Yes
ID of weak building elements	No	Yes
Flanking measurement	Marginal	Yes

Courtesy of Freytag & Associates.

One difference seen in the table is whether the sound source is diffuse for measurements. A loudspeaker is a more directional source when compared to flyovers, with the degree of difference dependent on the specifications of the speaker used as well as the location of the loudspeaker. Elevated loudspeaker measurements will provide a more diffuse sound source than those on a tripod, but neither will provide the coverage of a flyover, nor the time-varying angle of incidence.

The logistics and feasibility of each test for particular circumstances may be used as a determining factor in selecting the test to be used in the field. The use of a loudspeaker offers flexibility in testing times and requires less setup times. Consultants are able to ensure that extraneous noise from activity in the area do not affect measurements by testing when it is not an issue [23]. The flyover method requires sufficient number of aircraft flights during testing times, and the number of flyovers is limited for a set period. As such, testing is constrained by the timing and duration of flyovers; thus, extraneous sources can affect the measurements as is noted in the Table

2.4. The total duration of the test is dependent on the frequency of flights as well as the required amount of flights to gather a representative sample of the area. Since the indoor and outdoor SELs must be measured simultaneously for the flyover test, the microphones are limited to a single point measurement per flyover. A single point measurement does not provide a good representation of the diffuse sound field in the room, resulting in the indoor measurement to be subject to adverse room acoustic effects, such as pressure maximums or minimums from standing waves, as noted in Table 2.4 [23]. The loudspeaker test allows use of a moving microphone or the average of multiple fixed locations to more accurately measure the diffuse sound field.

Multiple measurements are taken for each of the techniques, but the number of measurements offers different benefits depending on the test. The aircraft flyover test requires multiple flyover events to be measured. Each flyover corresponds to a NLR, so a series of measurements provides various NLR values as well as the statistics of the measurements. The type of event (takeoff, approach, and landing), type of aircraft, and flight path should be recorded for each measurement to be used as an additional resource in reporting, but make it difficult to repeat a test. Averages of measurements performed at different source angles are typically used for an artificial noise source test. Since numerous measurements are performed with each test, it is possible to remove outliers in the measured values to more accurately calculate NLR.

2.5 Day-Night Average Sound Level

The Day-Night Average Sound Level (DNL) is the average sound level for a 24-hour period with a 10 dB penalty for sound levels occurring between 10:00 PM and 7:00

AM [29]. The penalty is placed to compensate for the aggravation that excess sounds cause people during the night. The DNL metric is supposed to be a weighted average of the sound level representative of a typical day over the course of the year including a penalty for noises occurring at night. DNL is used to separate the various regions near airports into noise contours on Noise Exposure Maps (NEMs). The area near airports is separated in 5 dBA increments starting with 65 dBA since that is the minimum exterior DNL required by sound insulation programs. The maps are used to identify the target NLR for residences based off of the region in which it is located. Figure 2.2 is an example of a noise contour map that was created as part of a study by the Hartsfield-Jackson Atlanta International Airport in 2007 [30]. Buildings located between the blue and yellow lines have a DNL between 65 and 70 dBA, while those between the yellow and red lines correspond to a DNL between 70 and 75 dBA. The area within the red contours has a DNL greater than 75 dBA and is deemed unacceptable for residential construction by the FAA through the 1992 guidance [4].

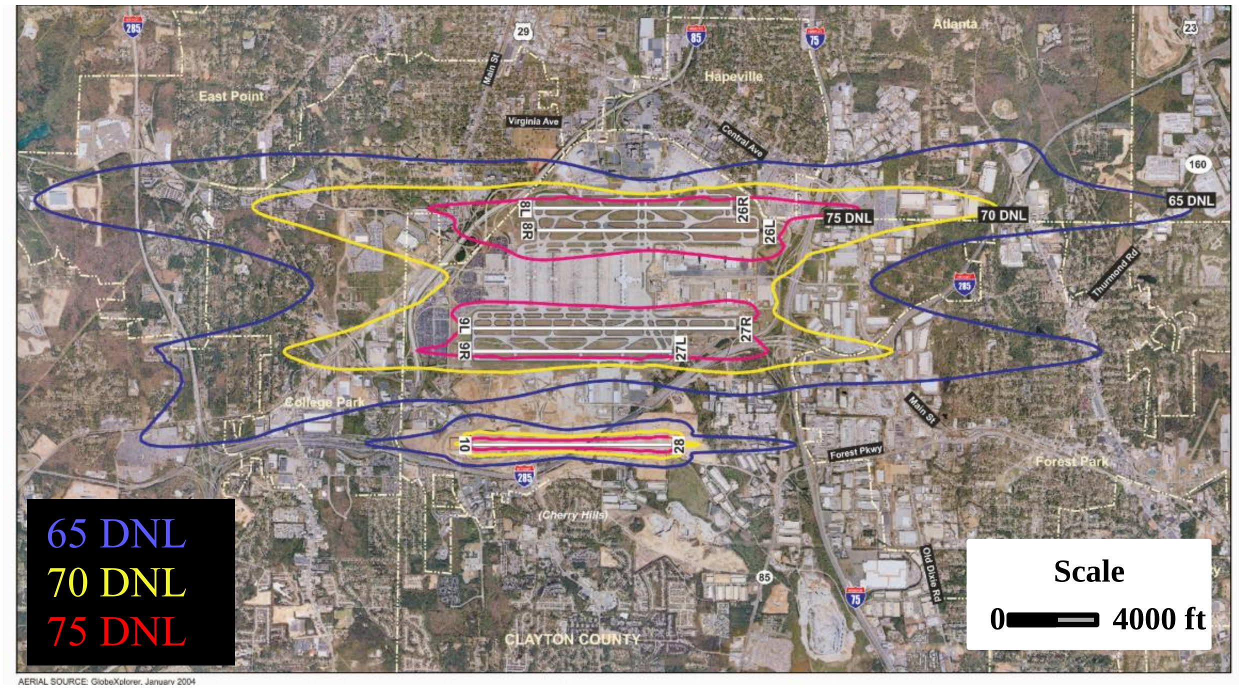
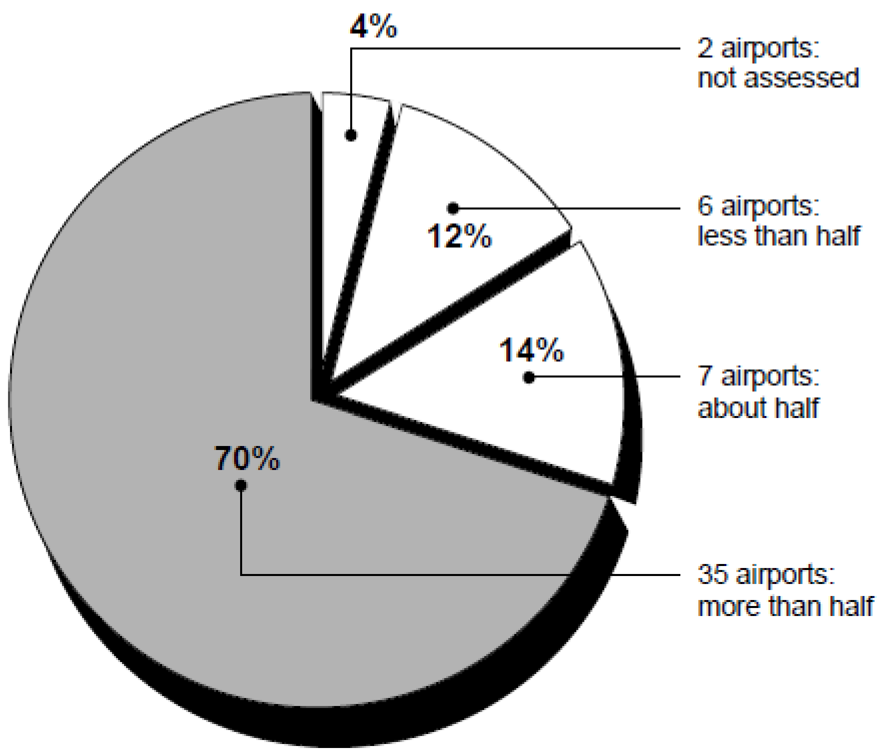


Figure 2.2: Noise contour map of Hartsfield-Jackson Atlanta International Airport modified from [30]

Although DNL is one of the main metrics in policy controlling aircraft noise, work is being done to see if there is an alternative metric that more accurately reflects community annoyance. One issue is that the program specifies the building must be within the 65 dBA DNL noise contour to be eligible, but thirty-five airports in a survey of fifty airports reported that more than half of the noise complaints they receive come from areas outside of the 65 dBA DNL noise contour [10]. Figure 2. 3 shows the portion of complaints that an airport receives from outside of the 65 dBA DNL noise contours. Another problem with the metric is that it is difficult for the community to understand and it may no longer be the best solution [1]. Mestre et al. determined in a report for the FAA that although DNL may not always be an ideal metric, replacing it with single event or cumulative noise metrics will not improve accuracy or precision [31]. However, Mestre et al.do provide a non-acoustic metric, Community Tolerance Level, and a metric that focuses specifically on low frequency noises, Low Frequency Sound Level, that may be beneficial in certain situations [31].



Note: Two airports have not calculated the portion of noise complaints that came from areas outside the 65 dB DNL contour.

Figure 2. 3: Portion of noise complaints located outside of the 65 dB DNL noise contours reproduced from [10]

2.6 Outdoor-Indoor Transmission Class

Outdoor-Indoor Transmission Class (OITC) is a single number rating used to quantify the isolation of outdoor sound by a building element or combination of elements. The procedure to calculate OITC is similar to that of NLR and is presented in ASTM 1332-10a [19]. The TL data of a structure is subtracted from the A-Weighted reference source spectrum presented in Table 2.5. The spectrum is an average of three typical spectra of aircraft takeoff, freeway, and railroad passby transportation sound sources [19]. The logarithmic sum of the difference is subtracted from the logarithmic sum of the unweighted source spectrum, 100.13 dB. Therefore, OITC is determined by

$$\mathrm{OITC} = 100.13 - 10 * \log \sum_{f} 10^{\left(\left(L_f - D_f + A_f\right)/10\right)} \ \text{[dB]}, \tag{2.5}$$

where, L_f is the reference source spectrum in Table 2.5 [19]. D_f is TL data in one-third octave band frequencies, and A_f is the A-weighting adjustment.

Table 2.5: Reference sound source spectrum reproduced from [19]

One-third Octave Band Center Frequency, Hz	Sound Level, dB
80	103
100	102
125	101
160	98
200	97
250	95
315	94
400	93
500	93
630	91
800	90
1000	89
1250	89
1600	88
2000	88
2500	87
3150	85
4000	84

ASTM E413-10 states that it is better to use OITC rather than STC for dealing with spectra such as machinery, musical instruments, or transportation noise. Therefore, OITC is a better metric to be used for external walls, but STC is still widely used due to its familiarity and prevalence.

CHAPTER 3

MEASURING VARIATION OF NLR MEASUREMENTS USING AN ARTIFICIAL NOISE SOURCE

The overall goal of this research is to better understand and improve methods of estimating Noise Level Reduction (NLR) with an artificial noise source for buildings exposed to aircraft. To accomplish this goal, a “test house” was built on Georgia Tech’s campus to provide a test article to measure the NLR of a building. The test house was built based off of the design of the one constructed in the hemi-anechoic chamber - as part of Thomas [22]. Some of the materials that were able to be salvaged from the original house were reused in the construction of the new outdoor test house. The test house was constructed outdoors to allow for a greater array of spatial positions for the loudspeaker placement than those that were available in the hemi-anechoic chamber. The source locations were selected at a variety of locations in the vertical and horizontal directions to better simulate the angular coverage of an aircraft flyover. The methods used to measure NLR were based off of the procedures provided in ASTM E966-10 [21]. Many acoustical consultants reference this document as the guide used to measure NLR; however, the standard does not specifically state the calculation of NLR.

3.1 Test House Construction

The final construction of the test house is seen in Figure 3.1. The test house was designed as a single-room structure with dimensions of 9’x10’x8’ high, with a volume of 720 ft^3. The dimensions and volume do not include the attic space. The structure was constructed on an area outside of the West Architecture Building on Georgia Tech's campus. The test house planning and construction was coordinated by Dr. Javier Irizarry in the College of Architecture. Volunteers from the College of Architecture and School of Building Construction assembled the house.

Figure 3.1: Final construction of completed test house

As discussed in section 1.1, the type of construction will have an impact on the sound insulation of a building. According to the Department of Energy (DoE), Georgia Tech, which is located in Fulton County, has a mixed-humid climate [7]. The house was designed with methods and constructed with materials typical of those of a mixed-humid climate as is seen in the building profile "Atlanta" provided by the DoE [8]. A crosssection of the “Atlanta” profile is seen in Figure 3.2. The walls of the test house were constructed with six layers from vinyl siding on the exterior to a layer of gypsum board on the interior. The list of materials and a sample of the construction are provided in Table 3.1. The test house contained vinyl siding, oriented strand board, and an asphalt-shingle roof in a raised heel roof truss as is seen in the profile in Figure 3.2.

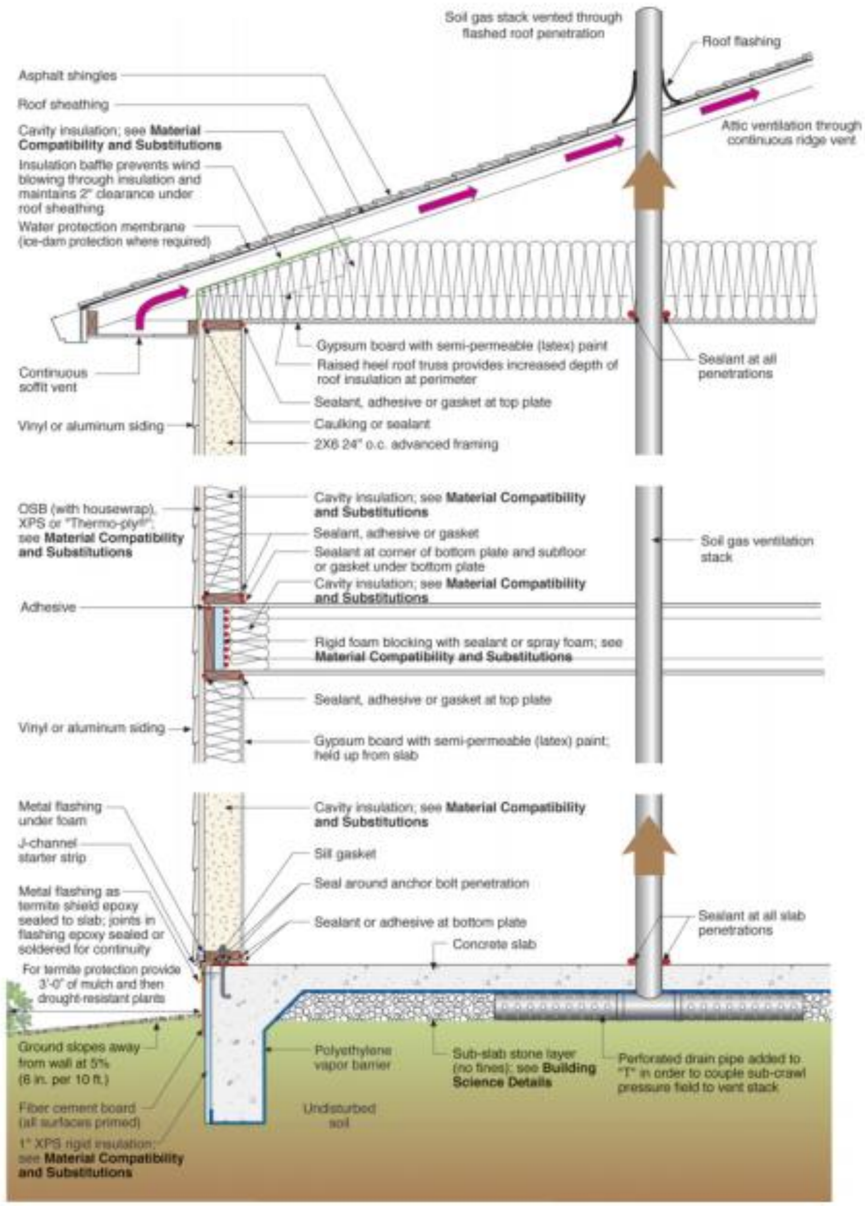
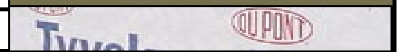
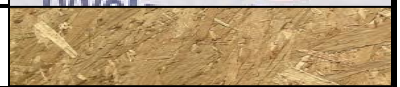
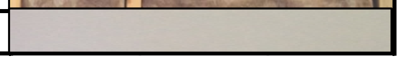


Figure 3.2: "Atlanta" building profile reproduced from [8]

Table 3.1: List of materials in wall construction of test house

Material	Picture
Fiber-Cement Siding (7/16")	
House Wrap	
Oriented Strand Board (7/16")	
2x4 Wood Framing @ 24" on Center	
3 1/2" Lay-in Fiberglass Cavity Insulation (R-13)	
1/2" Gypsum Board	

An attic space was constructed above the room in order to better simulate actual constructions in the area. The type of roof construction was selected to be raised-heel wood trusses in Thomas to allow for an easy comparison in modeling using IBANA-Calc; therefore, the same type of construction was used for this study [22]. The angle of the roof was such that there was approximately a three foot difference in height between the front wall and the rear wall of the house. The layers of the roof are presented in Table 3.2 with the asphalt shingles being the outermost layer while the gypsum board separated the room from the attic space.

Table 3.2: List of materials in roof construction of test house from outermost to innermost

Layer	Material
1	Asphalt Shingles
2	Roofing Felt
3	Oriented Strand Board (7/16")
4	Raised-Heel Wood Truss Framing
5	6 1/4" Lay-in Fiberglass Cavity Insulation (R-13)
6	1/2" Gypsum Board

Although the test house was modeled after typical construction, there were differences implemented in the design to better accommodate the research performed in Thomas as well as this one [22]. No door was included in the test house to maximize wall space and to simplify modeling performed in IBANA-Calc. An attic vent was also removed from the design to prevent possible flanking paths. The wall contained a 3’x5’ opening for a window; however, the opening was designed so that the window was easily interchangeable. This modification allowed windows of two Sound Transmission Class (STC) ratings to be used in the study. The window opening was used as the means of entrance since there was no door. Lastly, fastening of the house was mainly performed with screws rather than nails. Nails are more prevalent in typical construction since they offer a more permanent fastening. The use of screws allowed materials in the previous study to be salvaged for this one. Screws permitted the materials of this house to be deconstructed so that they could be reused. Although the screws are beneficial in the construction of the house, their use may introduce flanking paths to the structure. For example, nails may have helped reduce flanking paths such as the gap present in Figure 3.3.

Figure 3.3: Example flanking path on the exterior of the house

Once the exterior was completed, adjustments were implemented in the interior to better mimic an actual residence. An all-purpose joint compound was used to join adjacent sheets of gypsum board. Next, an insulating foam sealant was used to seal gaps that may have resulted in a flanking path. Lastly, acoustic insulation was added to the walls to better approximate the absorption present in a typical house. Insul-Quilt, an acoustic blanket with a fiberglass cloth backed with aluminum foil, was used to increase the absorption of the interior. The insulation was mounted to the wall in random areas using industrial strength Velcro. The Insul-Quilt was randomly placed on the inside of the room, as seen in Figure 3.4, to reduce the reverberation time to one more typical of a residence.

Figure 3.4: Example of random placement of Insul-Quilt mounted on a wall of the test house

3.2 Instrumentation

A variety of equipment and devices were used in taking sound level measurements on the test house. The instrumentation can be broken up into two categories based on its role in testing: sound source equipment and measurement devices. A list of the instrumentation used in the measurements is contained in Table 3.3. The equipment was selected to ensure compliance with ASTM E966-10 [21]. Figure 3.5 and Figure 3.6 depict the setup of the sound source equipment and the measurement devices respectively.

Table 3.3: List of equipment used in measurements

Instrument	Role
Peavey Impulse 12D Self-Powered Loudspeaker	Sound Source Equipment
Superlux Pink Stick Signal Generator	
Behringer MicroPower PS400 Phantom Power Supply	
15' XLR Cables	
Larson Davis 824 Sound Level Meter (SLM)	Measurement Devices
PCB Piezotronics 377A60 Condenser Microphone	
Larson Davis PRM 902 Preamplifier	
Larson Davis CAL200 Acoustic Calibrator	
UB1250 12V 5Ah Battery	

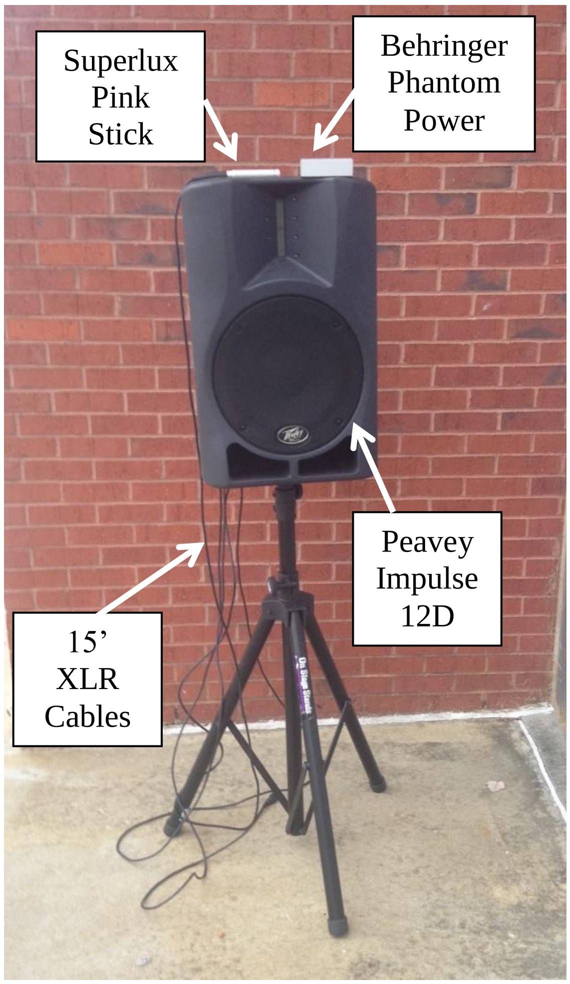


Figure 3.5: Picture of sound source equipment used in testing

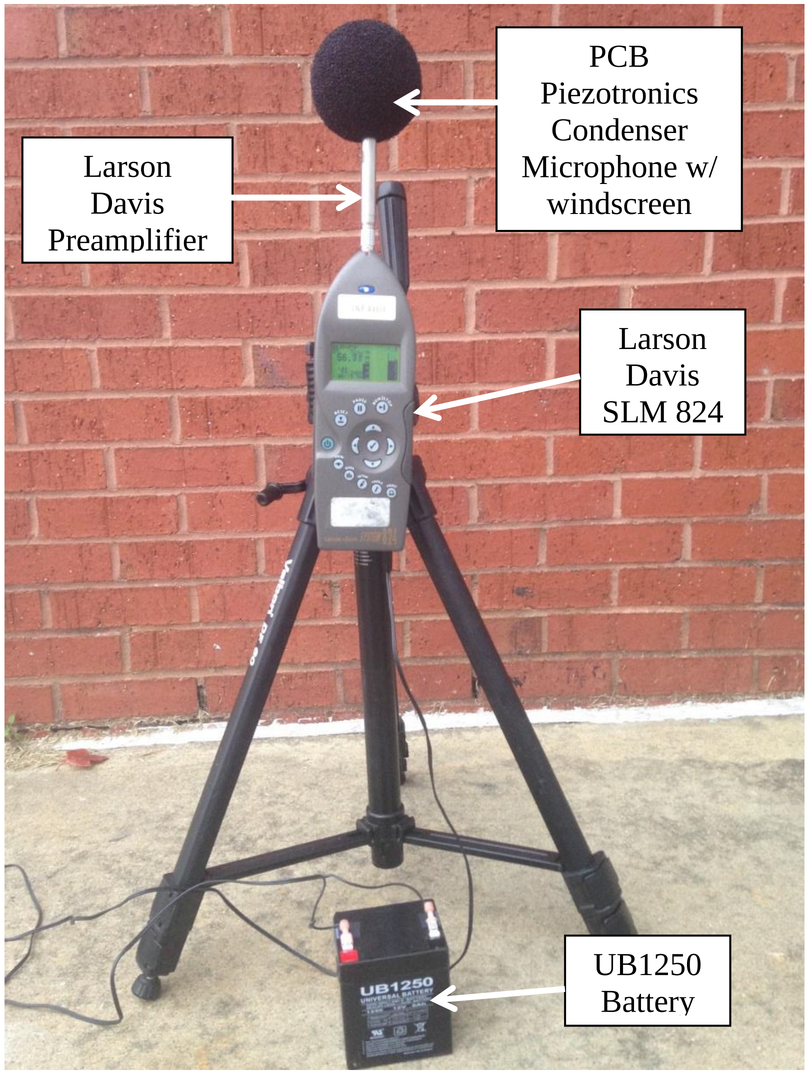


Figure 3.6: Picture of measurement devices used in testing

3.2.1 Sound Source

Thomas used a JBL EON 510 Self-Powered Loudspeaker in addition to the Peavey speaker listed above in Table 3.3 [22]. However, the Peavey Impulse 12D speaker was selected for these measurements since it exhibited a higher directivity than the JBL. The Peavey speaker has nominal radiation angles of 100° and 30° in the horizontal and vertical direction respectively. Particularly, the Peavey speaker was selected for this study due to its smaller vertical nominal radiation angle when compared to the 60° vertical radiation angle of the JBL speaker. Although the JBL speaker provided a more complete coverage of the structure vertically, it was believed the Peavey speaker would provide a noticeable difference in measurements at various source heights. The low frequency limit, provided by the manufacturer, is 60 Hz for the Peavey speaker; thus, NR values with 1/3 octave band frequencies below 63 Hz were not used in the calculation of NLR. Although the 63 Hz one-third frequency band contains frequencies below 60 Hz, the signal was greater than 10 dB above the background noise as required by ASTM E966-10 [21].

3.2.2 Pink Noise Signal

Pink noise was used as the signal for the loudspeaker, as is typically the case when using the loudspeaker test for measuring NLR [3]. Although NLR is dependent on aircraft spectra, pink noise is typically used to provide consistent NLR measurements in various tests. According to ASTM E966-10, the loudspeaker should produce a sound level of at least 5 dB above the ambient, or background, noise level from 80 to 4000 Hz [21]. If the signal is between 5 and 10 dB above the ambient level, a correction factor for background noise must be applied. The formula for the sound level of a measurement with a correction is

$$L_s = 10 * \log\left(10^{L_{sb}/10} - 10^{L_b/10}\right) \text{ [dB]}, \quad (3.1)$$

where L_s is the new adjusted signal level, L_{sb} is the combined signal and background noise level measured, and L_b is the background noise level. An ambient level was taken for measurements to ensure the signal level satisfied the background noise condition.

The pink noise signal generator was connected to the speaker and powered by the phantom power supply via 2 15' XLR cables. The phantom power supply was required to convert the 120 V AC power to the 48 V DC power required by the signal generator.

3.2.3 Sound Level Meters

As listed in Table 3.3 a Larson Davis 824 SLM (824), Larson Davis PRM 902 Preamplifier, and a PCB Piezotronics 377A60 Condenser Microphone were used for sound level measurements. Each system was calibrated with a Larson Davis CAL200 Acoustic Calibrator to ensure it correctly measured 140 dB at 1000 Hz before each use. The 824 meets the requirements of the ASTM E966-10 as it meets the Type 1 requirement set forth by ANSI S1.43 or IEC 61672 [21, 32, 33]. The measurements were completed using a Sound Spectrum Analyzer (SSA) program on the 824. The program recorded sound levels from 12.5 Hz to 20 kHz across 1/3 octave frequency bands with flat weighting as well as the equivalent sound level for each measurement. A windscreen was placed on the microphones to offer protection from the elements during testing.

3.3 Measurement Methods

There are three methods that were used when collecting NR values for the test house: fixed flush, fixed near, and moving. Both of the fixed methods were derived from ASTM E966-10 [21]. The interior moving method is mentioned in the standard; however, the procedure for the outdoor moving method based off of techniques used by consultants at Landrum & Brown (L&B).

3.3.1 Fixed Near

ASTM E966-10 provides a test method to calculate both the interior and exterior sound level measurements using the fixed near method [21]. Figure 3.7 provides a depiction of the geometric parameters and constraints on the fixed near method including sample microphone and source locations.

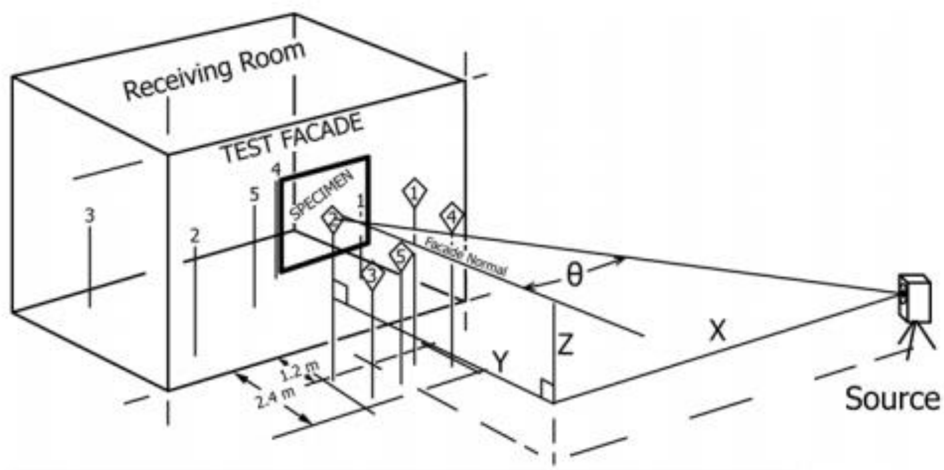


Figure 3.7: Geometry example of fixed near method reproduced from [21]

The restrictions of the exterior sound level measurements are specified in ASTM E966-10 to be at random distances and heights at a range of 1.2 m to 2.5 m from the test structure [21]. The microphone placements are to also lie within the outer bounds of the geometry of the test structure. The microphones were placed on tripods at three different heights of 3’1”, 4’3.5”, and 5’4.5”. There are a total of six positions and three heights for each position, resulting in eighteen total positions. The candidate microphone positions for the exterior measurements of the fixed near method appear as blue circles in Figure 3.8. Detailed drawings with the dimensions of the positions are available in Appendix A.

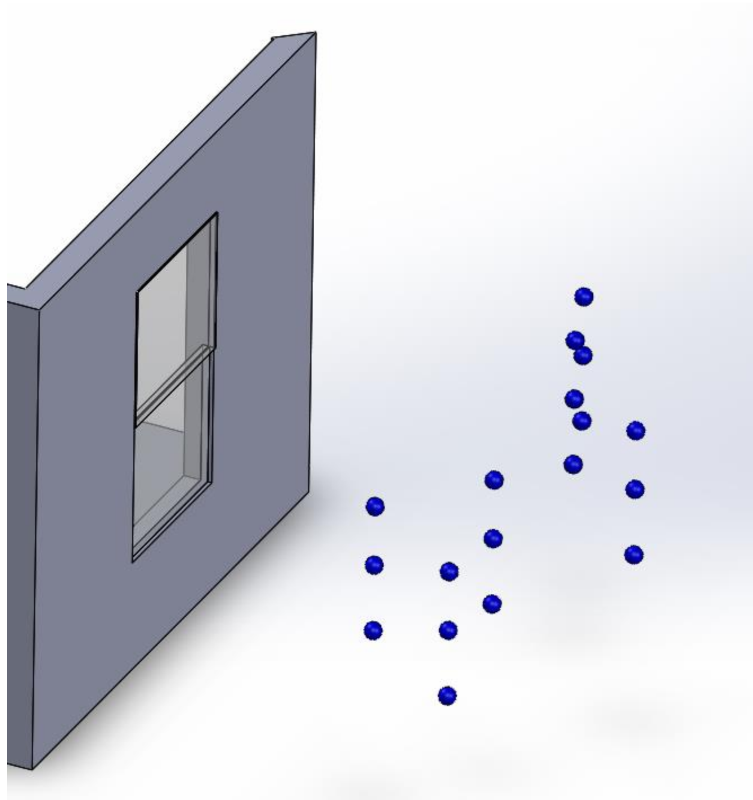


Figure 3.8: Candidate microphone positions for the exterior measurements of the fixed near method

According to ASTM E966-10, the procedure for the indoor sound pressure levels includes requirements for positions in relation to each other as well as to surfaces in the receiving room [21]. Ideally, no microphones are placed within a 1 m of a surface within the room or the other positions, but that distance is reduced to 0.5 m if the room is too small to satisfy this constraint; this is the case within the test house. The same three tripod heights (3’1”, 4’3.5”, 5’4.5”) used in the exterior measurements were also used in the interior measurements. Six random microphone positions were selected to be used for the study. The possible microphone positions for interior sound level measurements using the fixed near method are depicted in Figure 3.9. Appendix A also contains a detailed drawing of the microphone locations.

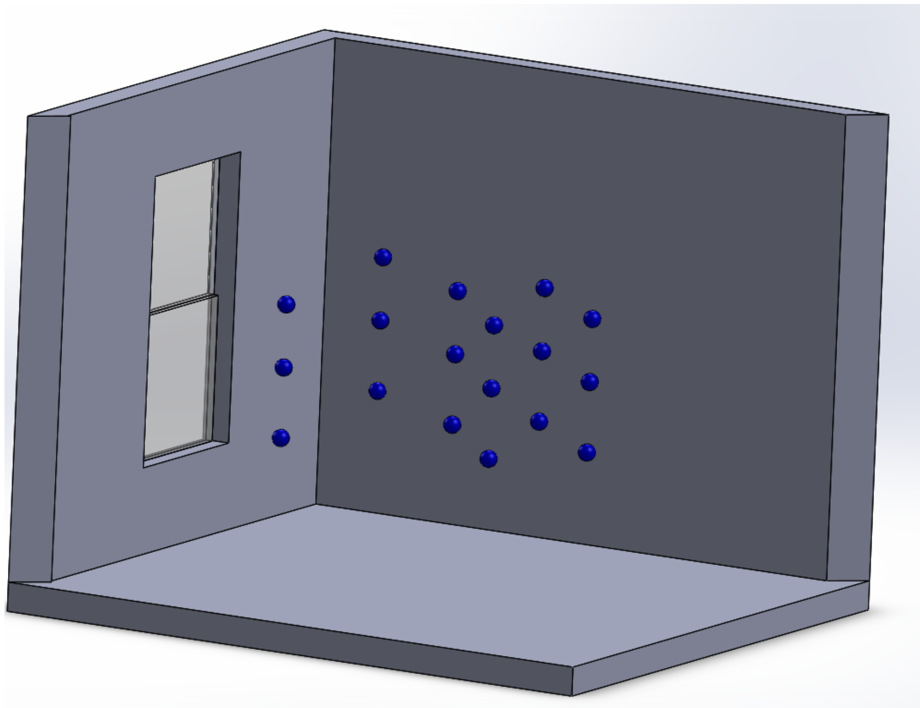


Figure 3.9: Candidate microphone positions of the fixed interior measurements

To perform a fixed near test, five locations were randomly selected for both the interior and exterior locations. A single measurement consisted of collecting thirty seconds of data simultaneously for the interior and exterior levels. Both the position and height were selected randomly for each point, with a total of five measurement positions selected per test. Due to the presence of the façade, a 2 dB correction factor is used to compensate for the near doubling of the sound pressure in the calculation of OINR(θ),

$$\text{OINR}(\theta) = L_{near} - L_{in} - 2 \text{ [dB]}, \tag{3.2}$$

L_{near} is the exterior sound pressure level measured using the fixed near method [21]. While L_{in} is the interior sound pressure level measured using fixed methods. The correction factor was originally 3 dB, corresponding to a theoretical doubling of sound pressure, but was found to be less in practice [34].

The fixed near method is considered less accurate that the fixed flush method. ASTM-E9660-10 suggests that the fixed near method should only be used when the fixed flush method is not feasible [21].

3.3.2 Fixed Flush

Another method to measure NR, using a loudspeaker, provided in ASTM E966-10 is the fixed flush method [21]. Figure 3.10 provides a depiction of geometric parameters and constraints on the fixed flush method including example source location and microphone locations for measuring the OINR of a window on a façade.

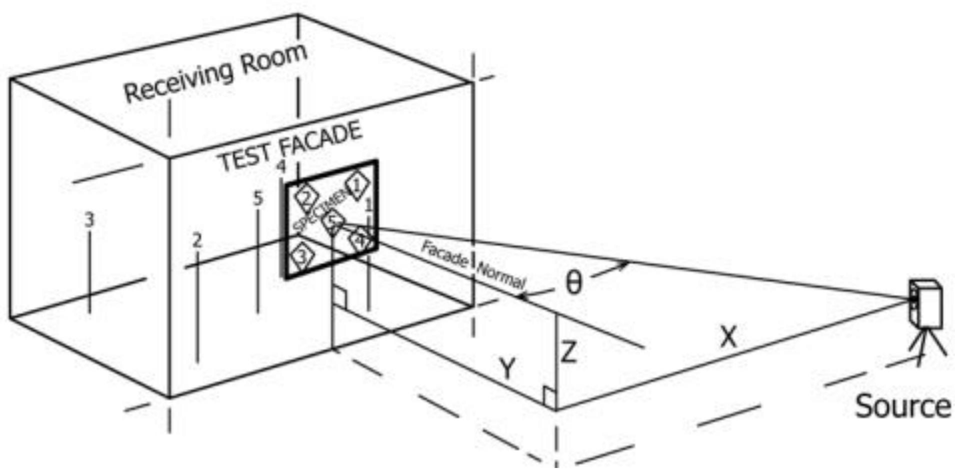


Figure 3.10:Geometry of fixed flush method reproduced from [21]

The exterior microphones for the fixed flush method are placed close to the façade without touching the façade or restricting the airflow through the microphone [21]. Six positions were selected along the façade of the test house without covering the surface area of the window as seen in Figure 3.11. The SLM tripods were used to position the microphone at its specific location for a measurement. The specific dimensions of the layout are provided in Appendix A. An example of a microphone in a fixed flush location is provided in Figure 3.12.

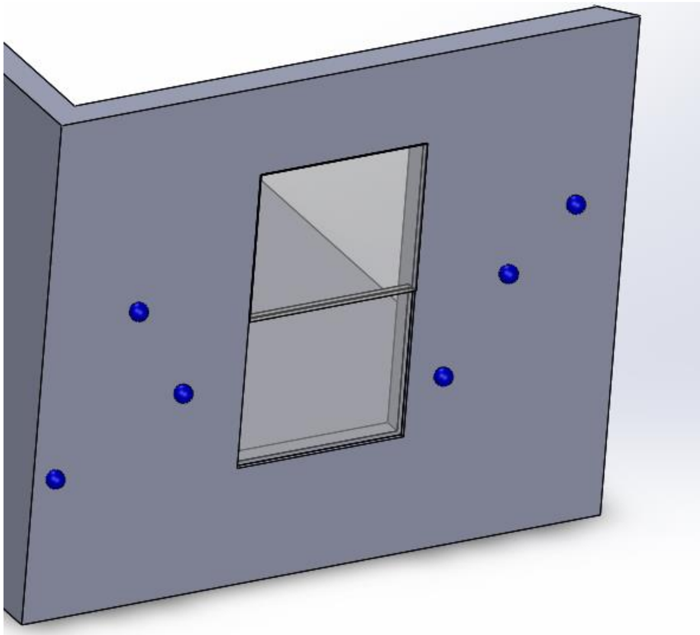


Figure 3.11: Candidate microphone positions for the exterior measurements of the fixed flush method

Figure 3.12: Example of fixed flush exterior sound pressure level measurement location

Five locations were randomly selected for both the interior and exterior locations to perform a fixed flush test. The interior sound pressure levels for the fixed flush method are measured in the same way and in the same positions as the fixed near method pictured in Figure 3.9. As was the case with the fixed near method, a test consisted of five simultaneous measurements of interior and exterior sound pressure levels for thirty seconds. Five of the six positions were randomly selected for the exterior measurements, while the position and height were randomly chosen for the interior measurements. The fixed flush method is only feasible for façades that are smooth and hard according to ASTM E966-10, as was the case for the test house [21]. The NR correction factor for the fixed flush method is 5 dB to account for the nearly quadrupling of the sound pressure from the proximity of the façade,

$$\text{OINR}(\theta) = L_{flush} - L_{in} - 5\,[\text{dB}], \tag{3.3}$$

where L_{flush} is the exterior sound pressure level measured using the fixed flush method [21]. Again, the correction factor was originally 1 dB higher in previous versions of the standard, but was reduced to 5 dB to better reflect measured results [34].

3.3.3 Moving

The last method examined in this study to measure NR with a loudspeaker is the moving method. The procedure for the moving method was derived based off a discussion with consultants at L&B, Alan Hass and Eric Seavey, and procedures mentioned in ASTM E966-10 [21]. A similar method was used as part of L&B's study at the BTV airport [20]. Figure 3.13 contains a freeze-frame of a moving method exterior measurement.

Figure 3.13: Freeze-frame of a moving method measurement

The exterior microphone measurements involve sweeping the microphone across the surface of the façade. The microphone was slowly swept while continually maintaining an approximate sinusoidal motion upholding a distance of about a meter away from the façade. Each measurement period lasted about forty seconds and involved sweeping the microphone across the façade four times, twice in each direction. The path was contained within the sides of the façade and between approximately 2’ to 7’ high. In addition, care was taken to never directly block the path from the sound source to the microphone. Figure 3.14 depicts an idealized example of a single typical path of the microphone for exterior sound pressure level measurements using the moving method.

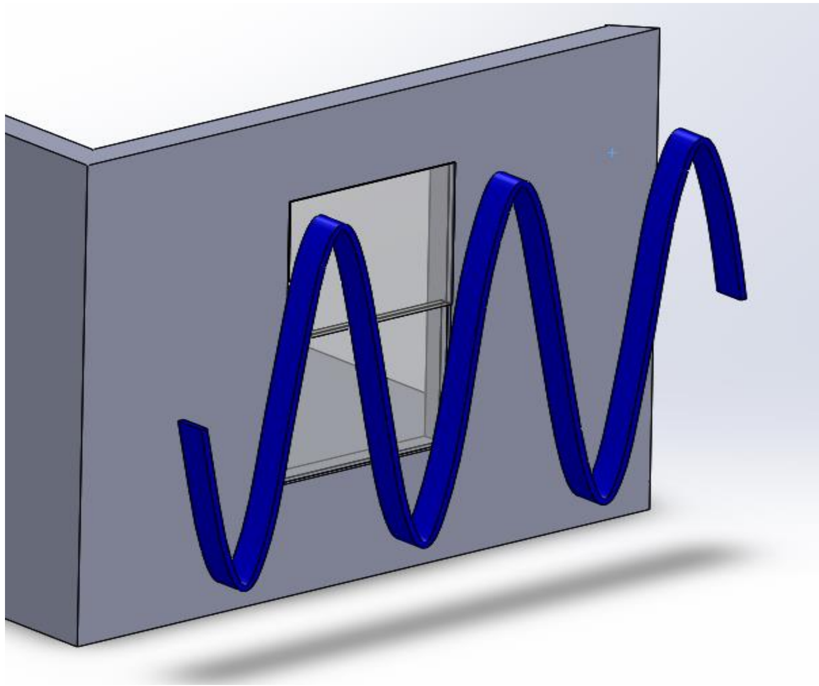


Figure 3.14: Example idealized path of exterior sound pressure level measurement using moving method

ASTM E966-10 mentions the option of "a single moving microphone manually swept or moving continuously along a circular path may be used… The minimum averaging time for a moving microphone shall be 30 s" [21]. Based off of this guideline and the help provided by L&B consultants, a moving method interior sound pressure level measurement procedure was developed. The microphone is slowly swept in a circular motion near the center of the room. Each measurement period lasted about forty seconds and included two laps of the room. The first lap placed the microphone about 0.5 m from the walls, and the second path moved the microphone closer to the user such that it was about 0.5 m from the center of the room. The microphone was swept in a circular path maintaining an approximate sinusoidal motion. Care was taken when moving to step lightly as to not add background noise with steps on the wood floor. An example of an idealized path for an interior sound pressure level measurement using the moving method is depicted in Figure 3.15.

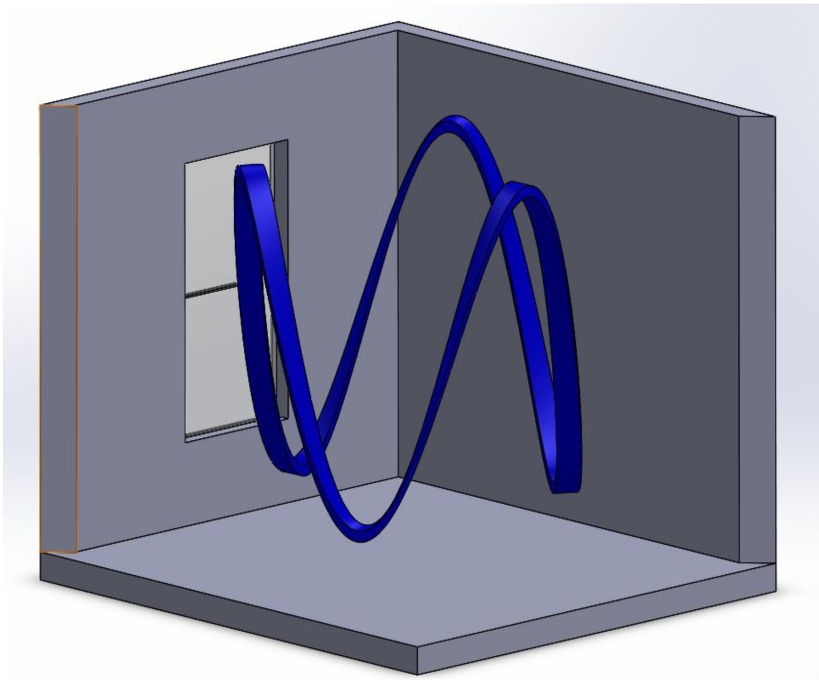


Figure 3.15: Example idealized path of interior sound pressure level measurement using moving method

A test of the moving method contained a single indoor and outdoor sound pressure level measurement, each lasting about forty seconds. Contrary to the two fixed methods, the moving method used sequential measurements rather than simultaneous indoor and outdoor measurements. Rather than moving the entire 824 unit when performing the sweeping motions, a Larson Davis EXA050 LEMO extension cable was used to connect the preamplifier to the 824. Calibration was performed with the LEMO extension cable attached before using the 824 for a moving method test. Since no NR correction factor is listed in ASTM E966-10, a correction factor of 3 dB was used based off of the advice of the L&B consultants. NR for the moving method is calculated using

$$\mathrm{OINR}(\theta) = L_{moving} - L_{in,m} - 3\,[\mathrm{dB}], \tag{3.4}$$

where L_{moving} is the exterior sound pressure level measured using the moving method and $L_{in,m}$ is the interior sound pressure level measured using the moving method. L&B uses this correction factor in their calculations; it was determined based off of field testing.

3.4 Measurement Procedure

All of the measurements performed in this study can be divided into four testing procedures: repeatability, reproducibility, tripod mounted speaker, and lift mounted speaker. While the repeatability and reproducibility test used a tripod mounted speaker, specific procedures were implemented to differentiate them from the tripod mounted speaker test. Statistical evaluations of the various methods were calculated with the repeatability and reproducibility tests. Once ninety-five percent confidence intervals for each method were determined, measurements were performed using the lift mounted and tripod mounted speaker. The lift mount offered testing up to 30' above the ground, but lateral movements were restricted due to its need to be placed on a hard surface. The tripod mounted speaker allowed for greater variations in horizontal angle of incidence and source offset distance, but was limited to a source height of 7'.

3.4.1 Repeatability Tests

Repeatability is defined as the ability for a measurement to be repeated multiple times using the same measurement test yielding comparable results. Repeatability correlates to the same acoustician performing the same measurement. Thus, it can be viewed as the statistical evaluation of the test method performed at various sites by the same person.

The repeatability test was performed with an angle of incidence of 45°, a source height of 3’5”, and a pink noise source. To test the repeatability of each method, an identical test was implemented five times in a row. Five random indoor and outdoor locations were selected for the fixed near method. Each of the five tests for the fixed near method used the same five locations for each test. The same procedure was used to test the repeatability of the fixed flush method; five random indoor and outdoor locations were used for five identical tests. For the moving method, five tests were taken with similar starting positions and paths.

3.4.2 Reproducibility Tests

Reproducibility is defined as the ability for various test configurations allowed within a procedure to yield comparable results. It can be viewed in the field as the statistical evaluation of various consultants attempting to implement the same procedure.

Reproducibility was measured under the same conditions as the repeatability test with an angle of incidence of 45°, a source height of 3’5”, and a pink noise source. However, instead of five identical tests with the same locations for the two fixed methods, random locations were selected for each of the five tests. It was difficult to distinguish repeatability tests and reproducibility tests for the moving method since there were no locations to randomize. Nevertheless, it was more difficult to implement the exact same tests in the moving method than the fixed tests since microphones are not able to be swept in identical paths.

3.4.3 Lift Mounted Speaker

Mounting the speaker on a lift is a common practice in NLR measurements. Since the loudspeaker is a substitute for aircraft flyovers, the lift typically offers a greater spatial array of source locations, especially vertically. The source heights achieved with the lift are a better simulation of the angular coverage from aircraft flyovers.

Georgia Tech Facilities provided the man lift pictured in Figure 3.16 for use in this study. Three different heights of 15’, 20’, and 30’ were achieved with the lift mounted speaker as seen in Figure 3.17. Appendix A provides the dimensions of the sound source for these tests.

Figure 3.16: Man lift used in lift mounted measurements

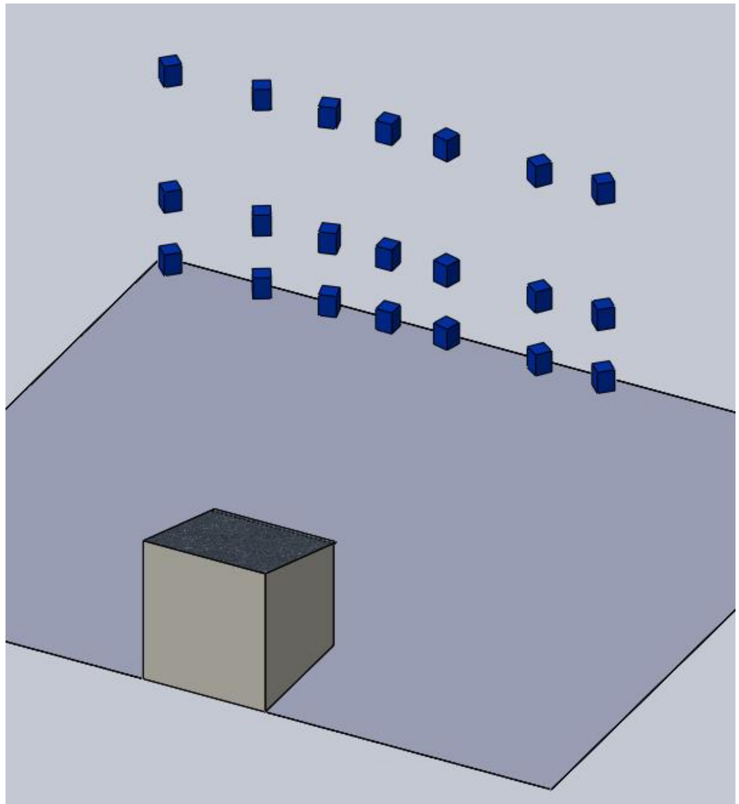


Figure 3.17: Lift mounted speaker locations from a rear view of the test house

The lateral movements of the lift were restricted due to columns of the Architecture West Building. The source offset distance was also restricted since the lift required a hard surface for support when in use. The speaker was mounted on a pole which was attached to the lift with c-clamps. The speaker was directed at the house in two orientations. The first orientation depicted in Figure 3.18a was used for the 20' measurements while the other orientation in Figure 3.18b was used for the other heights. The difference in speaker orientation was due to the orientation of the lift at the measurement locations. Before each measurement, the speaker was lined up to ensure that the center of the speaker was directed towards the center of the façade.

Figure 3.18: (a) 20' and (b) 15' and 30' lift mounted loudspeaker

3.4.4 Tripod Mounted Speaker

Tripod mounting is the simpler option for mounting a loudspeaker for NLR measurements. The tripod mount is especially applicable for single floor constructions or structures where the first floor has significant flanking paths [24]. The tripod allowed for a variety of spatial positions, specifically in the horizontal directions. Two tripods were used to mount the speaker via a pole mount, with one used at a height of 3’ 5” and the other used at 7’.

Figure 3.19 depicts all of the source positions for the tripod mounted speaker as viewed from the top of the house. Appendix A contains a detailed drawing with the dimensions for each test. The red speaker locations were the source locations varied radially, such that the source was equidistant from the center of the façade with altering horizontal angles of incidence. Measurements were also taken with the sound source at an equal offset from the façade, represented by the green speaker locations. The yellow speaker is the location where both tests were performed. Additionally, it was the location used for repeatability and reproducibility testing. Lastly, the blue speakers are the locations used for the lift mounted speaker testing. Measurements with the tripod-mounted speaker were also taken at these locations to compare against the lift mounted measurements.

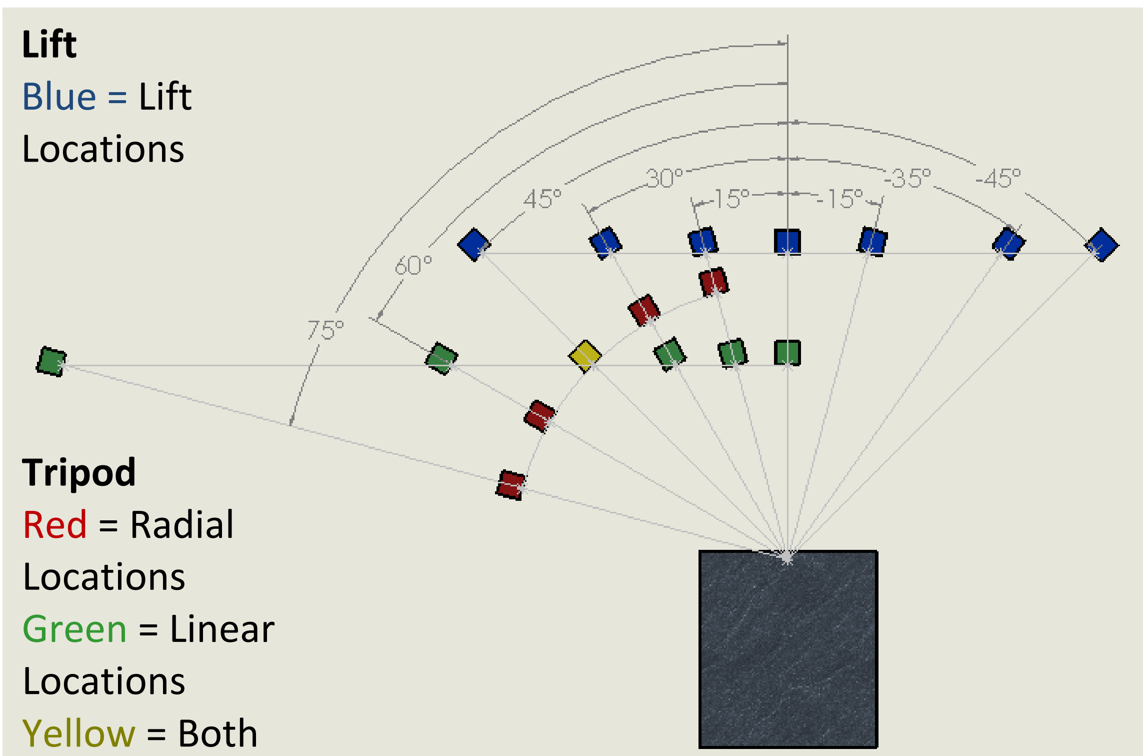


Figure 3.19: Tripod mounted speaker locations from a top view of the test house

3.5 Testing Iterations

A total of 197 different iterations were completed over the course of the project with 157 instrument iterations and 40 construction iterations. The effect of source parameters and microphone locations on NLR measurements were examined as part of the instrument iterations. The construction iterations analyzed the affect that the acoustical rating of the window and the window condition had on NLR measurements. The complete list of iterations is presented in Appendix B.

3.5.1 Instrument Iterations

The goal of the instrument iterations is to evaluate the affect that different geometric parameters have on NLR measurements. A specific focus was placed on evaluating the effect that the location of the speaker has on NLR measurements. The location of the source was altered in order to capture the greatest array of spatial positions in both the horizontal and vertical directions. A diffuse sound source was desired to best approximate the angular coverage of an aircraft flyover.

3.5.1.1 Horizontal Angle of Incidence

A total of nine different horizontal angles of incidence, θ, were examined, where θ is defined in Figure 3.20. The angles measured at the lift locations were 45°, 30°, 15°, 0°, -15°, -35°, and -45°. The 0° position is at the same offset distance as the rest of the measurements in the set; it is placed so the source is perpendicular to the façade. Data was taken at -35° rather than -30° to allow the lift to accommodate a column of the Architecture West Building. The linear and radial positions were varied from 0° to 75° in 15° increments.

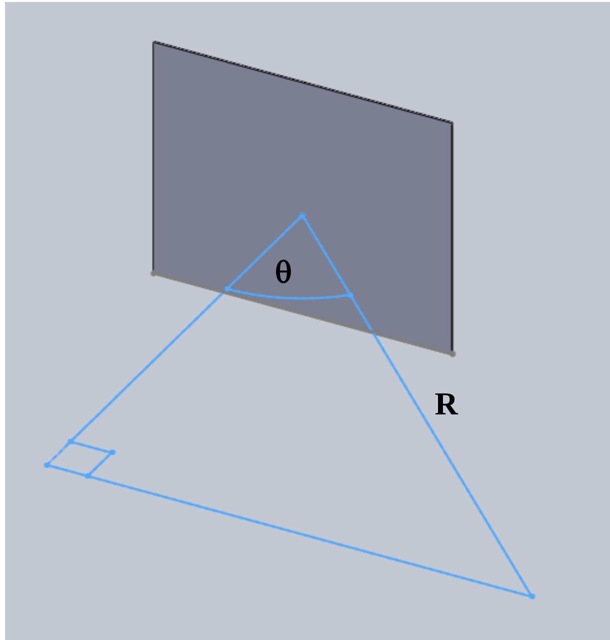


Figure 3.20: Diagram depicting the angle of incidence, θ

ASTM E966-10 states that it is preferable to choose an angle of incidence of 45° if the goal is to minimize the number of test conditions; however, measurements should be made at 15°, 30°, 45°, 60°, and 75° on a hemisphere if the field measurements are to be compared to those in a diffused sound field [21]. A special weighting is also required when making this calculation.

3.5.1.2 Source Height

Over the course of the measurements, the impact that the source height had on NLR measurements was analyzed by performing tests at five heights: 3'5'', 7', 15', 20', and 30'. Both the 3'5'' and 7' measurements used a tripod, while the other measurements used a man lift. The speaker at a source height of 30' is pictured in Figure 3.21a and the speaker at a source height of 15' is pictured in Figure 3.21b.

Figure 3.21: (a) picture with speaker at source height of 30' and (b) picture with speaker at source height of 15'

3.5.1.3 Source Offset

Three different source offsets were used in the study. The source offset is defined as the distance between the sound source location and the façade. Two of the distances are defined by the distance of a perpendicular line between the façade plane and sound source plane. The first offset is 10’4” for the linear locations and the second offset is 16’3” for the lift locations. The last offset is defined as the radius from the sound source to the center of the façade, such that each of the positions is equidistant to the middle of the house. The length of the radius is 14’7” for these locations.

ASTM E966-10 provides a restriction that the ratio of the distance from the source to the farthest side of the façade to the distance from the source to the nearest side is less than two [21]. An example case is depicted in Figure 3.22 with *R* being the distance from the source to the center of the façade, X_1 being the distance from the sound source to the farthest edge, and X_2 being the distance from the sound source to the nearest side. The sound source distance is acceptable as long as

$$\frac{X_1}{X_2} \leq 2\,. \tag{3.5}$$

Due to the relatively small distance across the façade of the test house, this condition did not affect testing locations.

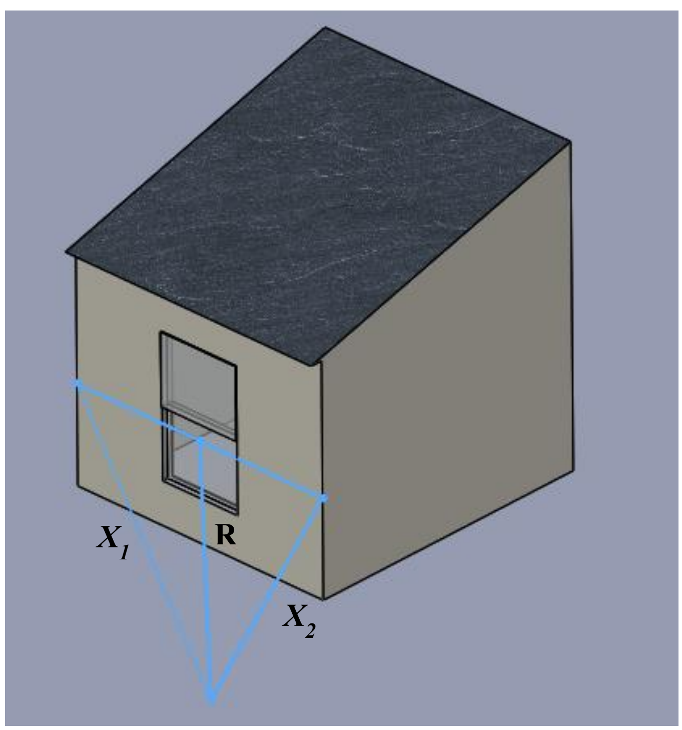


Figure 3.22: Example scenario to calculate minimum distance of sound source to test subject

3.5.1.4 Microphone Location

The last of the instrument iterations examined the effect that the microphone location, or measurement method, has on the NLR measurements. The three methods are discussed in detail in section 3.3. Each method was used in all lift mount testing measurements and most of the tripod mounted testing. Some of the tripod mounted testing only used the moving method to allow time for additional testing. The moving method was selected since it provided the most reproducible results, as is determined in section 4.1.2. By performing the same measurement with different microphone locations, a comparison between the methods is obtained and will be presented in section 4.1.

3.5.2 Construction Iterations

The smaller subset of iterations included the STC rating of the window and its condition. These iterations provided more of a check on the construction rather than an evaluation of measuring NLR.

3.5.2.1 STC Rating of Window

As mentioned previously, the test house was designed such that the windows were easily interchangeable. This modification allowed for testing with two different windows of varying acoustic performance. Both of the windows used in this study were 3’ x 5’ vinyl, single-hung Atrium Silent Guard® windows. The first window had an STC rating of 25 and the second window had an STC rating of 31. The specific properties of each window are presented in Table 3.4.

Table 3.4: Properties of test house windows

STC Rating	Glazing	Gap/Space	Glazing
25	3/32"	9/16"	3/32"
31	1/8"	13/16"	1/8"

3.5.2.2 Window Condition

The last set of iterations was performed to ensure that the NLR results measured in the field made physical sense compared to the theory. This was done by altering the window between three conditions: closed, ½ open, and open. Theoretically, an opening in a wall has a significant impact on the transmission loss of the wall, as was discussed in section 1.1; thus, as the surface area of the opening increased the NR should have decreased substantially. The test was done for each window; but only performed with the moving method at the 45° location with a 10’4” offset.

CHAPTER 4

EVALUATING VARIATION OF NLR MEASUREMENTS USING AN ARTIFICIAL NOISE SOURCE

4.1 Method Comparison

Before measurements were performed to evaluate the parameters of Noise Level Reduction (NLR) measurements, it was important to determine the statistics of the measurements. Repeatability tests and reproducibility tests were implemented using the procedures presented in sections 3.4.1 and 3.4.2 respectively. Confidence intervals (CI) were calculated to evaluate the precision of each the three measurement methods (fixed near, fixed flush, moving) examined in this study. The statistical results will also help evaluate other variations in testing. Repeatability can be seen as the precision of the same acoustic consultants implementing a standardized test, while reproducibility is the precision of different consultants implementing a standardized test.

The 95% CI for the NLR calculation of both the repeatability and reproducibility tests were calculated by determining the logarithmic average,

$$L_{avg}(i) = 10 * \log\left(\frac{1}{N}\sum_i 10^{L_{i/100}}\right) \text{ [dB]}, \tag{4.1}$$

and 95% CI from the NR measurements of the five tests. Here, N is 5 for the number of tests, L_i is the sound pressure level for the ith measurement, and L_{avg} is the average sound pressure level for the measurements. Maximum and minimum NR values are determined by adding and subtracting the 95% CI from the average NR respectively. Corresponding

NLR values are calculated for the maximum and minimum NR values using the calculation in section 2.4.1. The NLR 95% CI was calculated using

$$\text{NLR 95\% CI} = \frac{\text{NLR}_{max}\text{-NLR}_{min}}{2} \text{ [dB]}, \tag{4.2}$$

where NLR_{max} is the statistical maximum NLR value and NLR_{min} is the statistical minimum NLR determined from the 95% CI NR values.

4.1.1 Repeatability

Through testing, it was determined that the fixed flush method provided the most repeatable results, with a 95% CI of ±0.3 dB. The repeatability CI for the other two measurements was determined to be ±0.5 dB. Table 4.1 includes a summary of the five tests and the calculated 95% CI for the repeatability test. ASTM E966-10 states that the near method should only be used when the fixed flush method is not feasible; therefore, it was expected that the fixed flush method be more repeatable than the fixed near method [21]. The moving method introduces more variation from measurement to measurement since it requires a human element, so it could also be seen that it would be less repeatable than the fixed flush method.

Table 4.1: Summary of repeatability test

	NLR [dB]		
	Fixed Flush (FF)	**Fixed Near (FN)**	**Moving (M)**
Set 1	17.9	17.3	16.9
Set 2	18.3	17.5	16.6
Set 3	18.4	17.6	16.0
Set 4	18.4	17.6	16.8
Set 5	18.2	17.3	16.3
Average	18.3	17.5	16.6
±95% CI	0.3	0.5	0.5

4.1.2 Reproducibility

Since NLR measurements determine whether a building is eligible for sound insulation programs, knowing the confidence of the measurements should reduce the margin of error. Reproducibility should provide a more useful precision metric since it relates measurements of a procedure rather than identical tests. The reproducibility CI could be applied to measurements of NLR in the field such that the interior Day-Night Average Sound Level (DNL) is more accurately represented.

Results of the reproducibility test are shown in Table 4.2. The moving method was determined to be the most reproducible test of the three methods with a 95% CI of ±0.5 dB. The fixed flush method had the second highest 95% CI with a value of ±0.8 dB, and the fixed near method had the lowest 95% CI with a value of ±0.9 dB. Although the moving method was not as repeatable as the other methods due to the human variation, it required less variation in reproduction of test-to-test measurements than the fixed methods. The fixed methods are more likely to be subject to room acoustic affects, depending on the location of the interior sound level meter (SLM) for a measurement. The averaging of five points helps combat this, but the moving method more accurately measures the diffuse field [23].

Table 4.2: Summary of reproducibility test

	NLR [dB]		
	Fixed Flush (FF)	**Fixed Near (FN)**	**Moving (M)**
Set 1	19.2	16.8	16.3
Set 2	19.4	17.8	15.7
Set 3	20.0	16.1	16.8
Set 4	19.6	17.7	16.2
Set 5	19.2	18.2	16.4
Average	19.6	17.5	16.4
±95% CI	0.8	0.9	0.5

The Schroeder frequency (f_s) was calculated with the added absorption to determine the lower frequency limit for which the room would contain fairly diffuse fields. Reverberation measurements were collected using the real-time analyzer (RTA) program on the sound level meter (SLM). The SLM calculates the reverberation time (RT_{60}), the time that it takes the signal to decay 60 dB in the room once a signal is shut-off. The RT_{60} for the room in the 1000 Hz full octave band was 0.248 s. The f_s of the room was calculated as

$$f_s = 2000\sqrt{\frac{RT_{60}}{V}} \text{ [Hz]}, \tag{4.3}$$

where V is the volume of the room [22]. The f_s was calculated to be 220.7 Hz for the test house room. Measurements below the f_s may be subjected to standing waves as there is not a consistent diffuse field present at these frequencies.

As mentioned previously, reproducibility is the better metric to use when placing confidence bounds on a measurement since it is applicable for a broader range of measurements. Therefore, the reproducibility 95% NLR CI values presented in Table 4.2 are used in the rest of the report when presenting error bars. Figure 4.1 plots the data from the table including the 95% CI as the error bars for each method and the average NLR as straight lines for each measurement. All of the measurements for the fixed flush and most of the moving method measurements lie within the CI from the average of the test, which is a way to confirm the accuracy of the confidence interval. Since no parameters of the method were changed between measurements, ideally all of the measurements within a method would have been the same. For field testing, measurements should be within a CI of its respective average, assuming that the average is the correct NLR value, to ensure each measurement was precise.

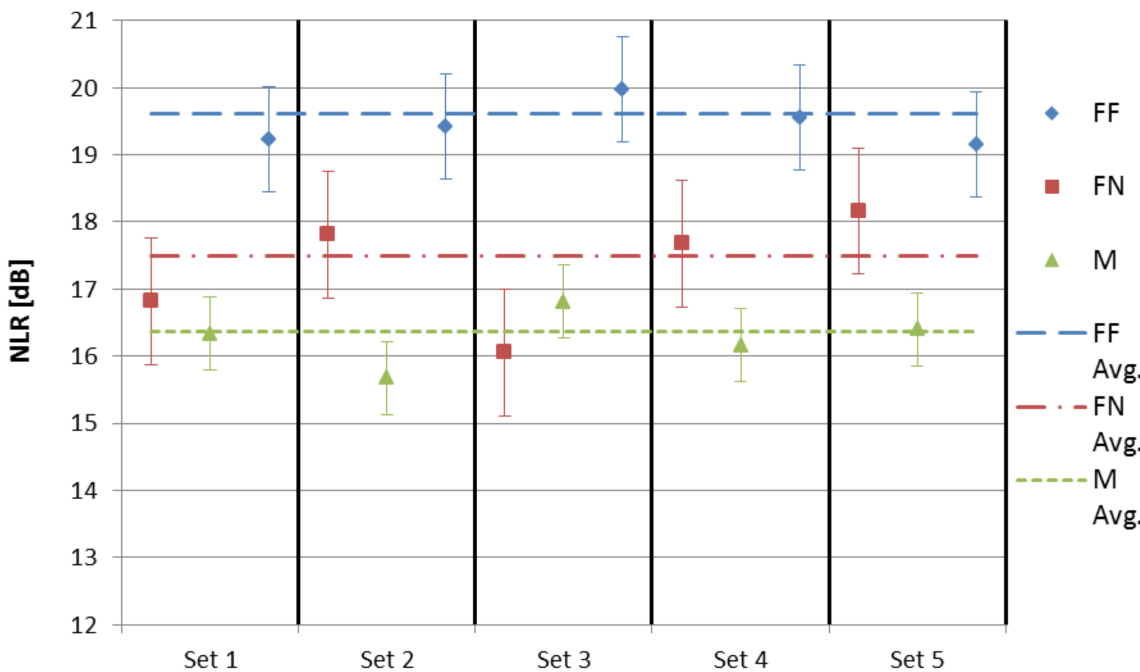


Figure 4.1: NLR values obtained for reproducibility test

4.2 Angle of Incidence

Once each method of testing was statistically evaluated, other parameters such as the angle of incidence were examined. The angle of incidence was altered both horizontally and vertically to achieve a large array of spatial positions in testing. The horizontal angles of incidence were altered from -45° to 75°. The vertical angle of incident was varied from 0°, such that the sound source was on the same plane as the center of the house (3'5"), to 58.6° (30').

4.2.1 Tripod Mount

4.2.1.1 Radial Variation

The horizontal angle of incidence was altered on a radius such that the speaker remained equidistant from the center of the house with varying angles. ASTM E966-10 states that measurements can be made at equal angles of incidence on a radius and weighted for comparison [21]. Radial variation testing with the speaker mounted on a tripod was performed at 3'5" and 7' from in 15° increments from 15° to 75°. Table 4.3 presents the data measured during radial testing with STC 25 window. The data is divided into six sections: 3'5" fixed flush, 7' fixed flush. 3'5" fixed near, 7' fixed near, 3'5" moving, and 7' moving. Each of the sections ranks the NLR values from red to green with red corresponding to the lowest values and green to the highest values. Ideally, all of the 15° measurements would have the highest NLR values with a green color, and the NLR values would gradually decrease with the lowest value at 75° since intensity of the transmitted wave typically decreases at increasing angles of incidence. It appears that both of the fixed flush tests and the 3'5" tests for the moving and fixed near method follow this trend. However, the change in NLR values from 15° to 45° is not significant for any of the tests, as the change is less than 3 dB. Further, five of the six tests measured NLR values that varied by less than 1 dB at these angles of incidence, while the 7' fixed near test measured NLR values span a 1.5 dB range. The measurements spread a range of 4 dB across all methods and source positions. The fixed flush method had the greatest range spanning 4 dB, while fixed near spanned 2.7 dB and moving 2.8 dB. Figure 4.2 plots the data for the radial locations with the STC 25 window to examine if any trends are visible graphically. At 75°, the NLR values are lower for the 3'5" moving, 7' fixed flush, and 7' moving tests. This drop in NLR value can most likely be attributed to the side façade affecting the NLR measurement of the front façade. At this angle, the speaker is approaching grazing, so it was also difficult to line up the speaker to the center of the building. The relation between the two source heights can be examined in addition to the horizontal angle of incidence. The average NLR values measured with the source at 7' were less than the average NLR values measured with the source at 3' 5". Contrary to expectations and to the other tests, the NLR values from the 7' fixed near test increase as the angle of incidence increases. Testing with the moving test produced an average NLR that was about 1 dB less than the other two methods. One possible cause for this could be an incorrect correction factor.

Table 4.3: Summary of radial locations with STC 25 window

	NLR [dB]		
	Fixed Flush (FF)	**Fixed Near (FN)**	**Moving (M)**
3'5'' 15 °	18.8	18.8	17.3
3'5'' 30 °	18.6	18.1	17.0
3'5'' 45 °	18.2	17.8	17.3
3'5'' 60 °	17.4	17.6	16.6
3'5'' 75 °	16.6	17.2	16.2
7' 15 °	18.4	16.1	16.8
7' 30 °	18.4	16.8	16.1
7' 45 °	17.5	17.6	15.9
7' 60 °	16.9	18.5	16.6
7' 75 °	14.8	18.4	14.6
3'5'' avg	18.0	17.9	16.9
7' avg	17.4	17.6	16.1
all avg	17.7	17.8	16.5

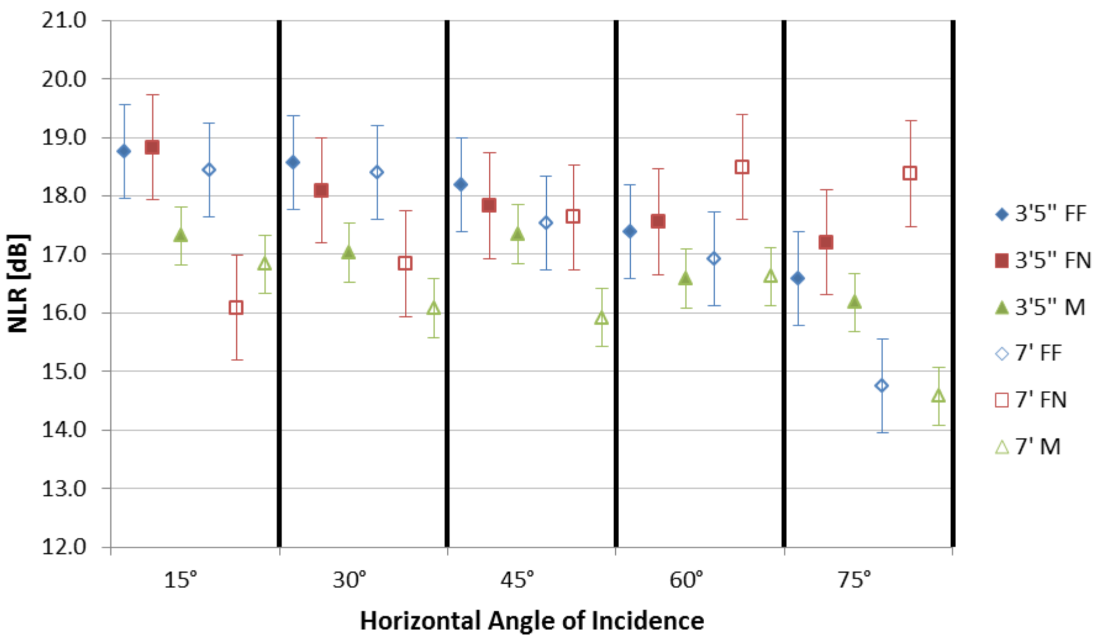


Figure 4.2: NLR values for radial locations of tripod mounted source with STC 25 window

4.2.1.2 Linear Variation

In addition to examining the angle of incidence by altering the source mounted on a tripod radially, a linear group of locations was also examined. Figure 4.3 plots the NLR values for the linear and radial locations with a 3’5” sound source and a STC 25 window measured with the moving method. The NLR values at the linear locations were only measured with the moving method since it was deemed the most reproducible method. The linear locations were measured with the loudspeaker at an offset distance of 10’4” and the radial locations were measured with the loudspeaker at a radius of 14’7” from the center of the façade. The measured NLR at the linear locations exhibit a greater drop-off with increasing angle of incidence than the NLR measured at the radial locations. At 75°, the measured NLR at the linear location was 2.8 dB less than the NLR measured at the radial location. The drop-off is expected for the linear locations since the radial distance to the façade increased significantly as well, as the source is located 39’11” radially from the center of the façade. An average of a 1 dB drop-off in NLR was measured between the testing at the radial and linear locations.

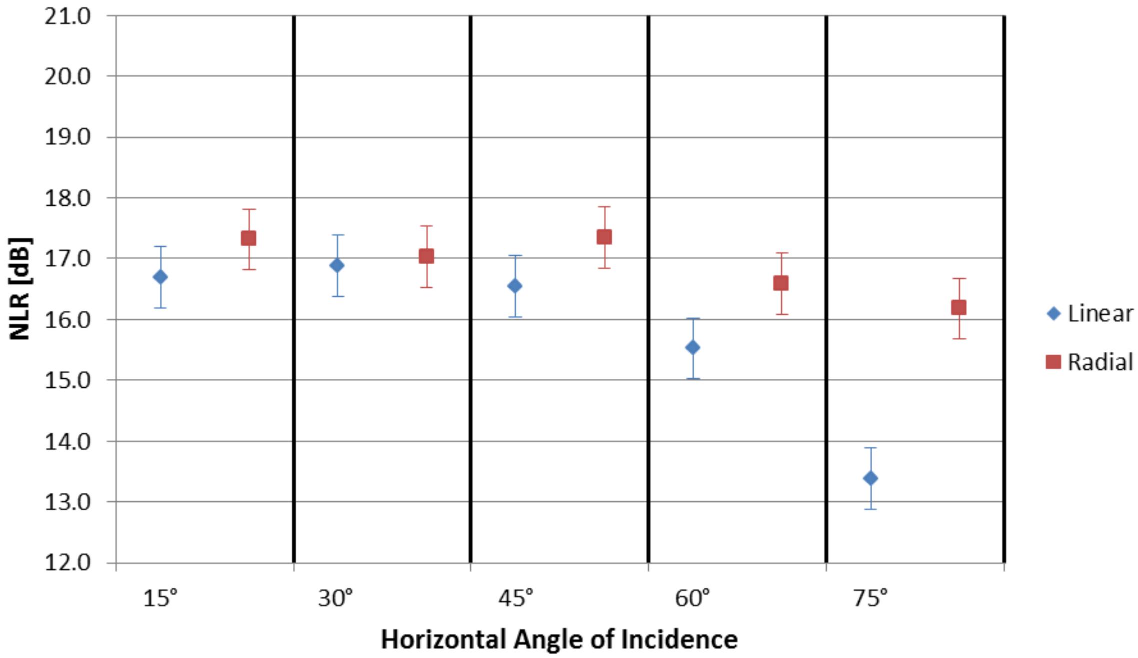


Figure 4.3: NLR values for the linear and radial locations for 3'5" source with STC 25 window and moving method

4.2.2 Lift Mount

A man lift was used to achieve higher source heights than those that were available with the tripods. Heights of 15', 20', and 30' were used to provide greater angular coverage of the façade by the loudspeaker and to better simulate the exposure of aircraft flyovers. This test continued to look at horizontal angle of incidence, but also examined increasing vertical angles of incidence and symmetry of measurements.

The summary of NLR values are presented in Table 4.4. The measurements are again color coded, such that the green values are highest and red values are the lowest, and divided in sections of height and method. Theoretically, the normal incidence measurement at 0° should have the highest NLR value. As mentioned previously the transmission of the pressure wave typically decreases at increasing angles of incidence, thus the NLR should decrease as the absolute value of the angle increases. However, this is not the case as a number of the sections of measurements contain the highest NLR at either 45° or -45°. Once again the moving method average NLR was about 1 dB below the fixed flush method average NLR, but this time the fixed near method average NLR was closer to the moving method average NLR than fixed flush average NLR.

Table 4.4: Summary of lift mounted speaker measurements

	NLR [dB]		
	Fixed Flush (FF)	**Fixed Near (FN)**	**Moving (M)**
15' 45°	17.5	14.7	17.1
15' 30°	17.7	16.0	16.6
15' 15°	18.0	16.5	15.9
15' 0°	17.5	16.8	16.1
15' -15°	17.2	15.3	15.9
15' -35°	18.3	16.8	16.3
15' -45°	18.2	18.3	16.9
20' 45°	15.8	15.4	15.1
20' 30°	17.7	17.3	15.5
20' 15°	18.7	16.3	16.3
20' 0°	17.0	15.8	16.1
20' -15°	17.6	18.5	15.8
20' -35°	17.2	16.6	17.0
20' -45°	17.5	16.7	17.3
30' 45°	16.3	14.1	14.6
30' 30°	16.1	14.5	16.6
30' 15°	17.0	15.2	16.7
30' 0°	17.4	16.8	17.0
30' -15°	17.1	15.1	16.7
30' -35°	17.6	16.7	16.8
30' -45°	17.9	16.2	17.2
15' avg	17.8	16.5	16.4
20' avg	17.4	16.8	16.2
30' avg	17.1	15.6	16.6
all avg	17.4	16.3	16.4

Ideally the test house construction is symmetric resulting in measured NLR values that are symmetric to the normal incidence measurement, but this is generally not the case. Table 4.5 presents the average NLR values for the positive and negative angles at each height. The positive and negative measurements are within 0.2 dB for the 15’ fixed near, 20’ fixed near, and 15’ moving tests; however, the measurements differ by about 1 dB for the others.

Table 4.5: Average NLR values for positive and negative angles

NLR [dB]			
	Fixed Flush (FF)	**Fixed Near (FN)**	**Moving (M)**
15' +° avg	17.7	15.8	16.5
15' -° avg	17.9	17.0	16.4
20' +° avg	17.6	16.4	15.7
20' -° avg	17.5	17.4	16.8
30' +° avg	16.5	14.6	16.1
30' -° avg	17.5	16.1	16.9

The ranges of each test were examined in Table 4.6 to see if any of the tests provided more consistent results. The measurements span a range of 4.6 dB across all methods and heights. The moving method has the lowest range of NLR values at 2.7 dB, but the 15’ fixed flush test has the lowest range for an individual test. The height does not appear to have an effect on the range of the measurements as the 30’ measurements have the smallest range, but there is no difference in total range between the 15’ and 20’ sources. The fixed near method had the largest total range in NLR measurements out of the three methods, as was expected based on the repeatability and reproducibility testing.

Table 4.6: Ranges for lift mounted speaker measurements

Range [dB]				
	Fixed Flush (FF)	**Fixed Near (FN)**	**Moving (M)**	**Total**
15'	1.0	3.6	1.2	3.6
20'	2.9	3.1	2.2	3.6
30'	1.8	2.7	2.6	1.8
Total	2.9	4.4	2.7	4.6

Lastly, a plot of all of the measurements performed with the lift was examined in Figure 4.4. While the NLR values measured with the fixed near and fixed flush methods are generally more irregular with their spread, it appears that the moving method NLR values remain fairly consistent across all angles of incidence. The one exception to this generalization is for the 45° angle of incidence measurements with the moving method since there is about a 2 dB difference between the 15' tests and the others, but all of the other angles remain fairly unchanged with variations in angle of incidence as is especially true for the 30' moving test. The plot also confirms that the house does not exhibit symmetry. The lack of symmetry in the measurements is likely due to flanking paths present in the construction.

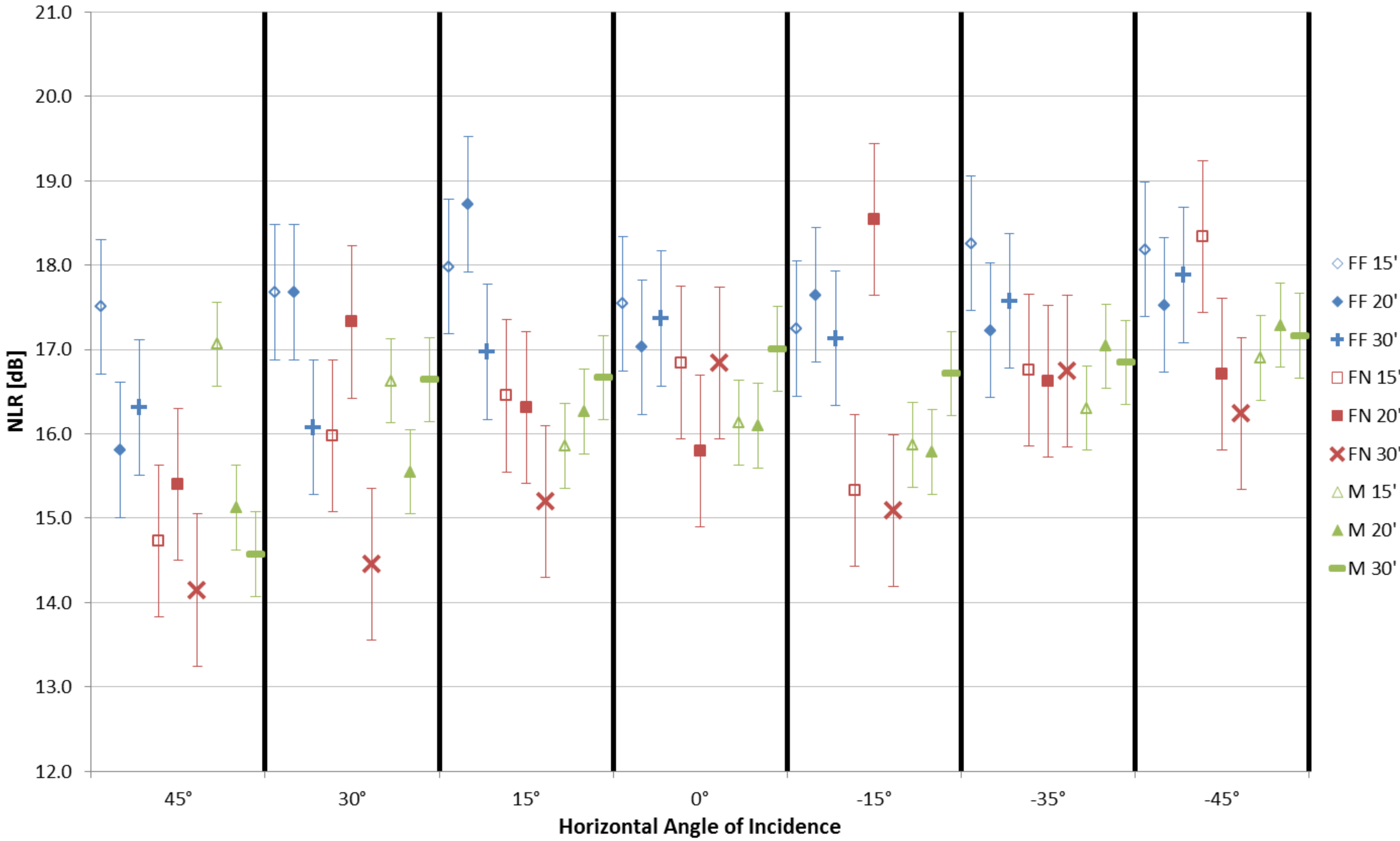


Figure 4.4: NLR values of the lift mounted speaker measurements

Looking at Table 4.4, the average NLR values measured with a source height of 30’ by the fixed flush method and fixed near method were less than the NLR values measured with a source height of 15’ and 20’. While the speaker was elevated to 30’, the coverage appeared to be directed over the roof of the house more so than the other heights due to limitations in mounting the speaker on the lift. The model pictured in Figure 4.5 and Figure 4.6 was created to represent the coverage of the speaker mounted on the lift at 30’ on the house, with the angular coverage defined by the nominal radiation angles of the speaker. Thus, the NLR may be lower at 30’ since the façade of the house falls outside of the path of the speaker resulting in lower exterior measurements in addition to more exposure by the roof of the structure. The NLR values measured with the fixed near method had the largest difference between the measurements with a source height of 30’ and the measurements with a source height of 15’. The fixed near method is likely most affected by the coverage of the speaker since the microphone locations are furthest away from the façade with this method when compared to the other two methods.

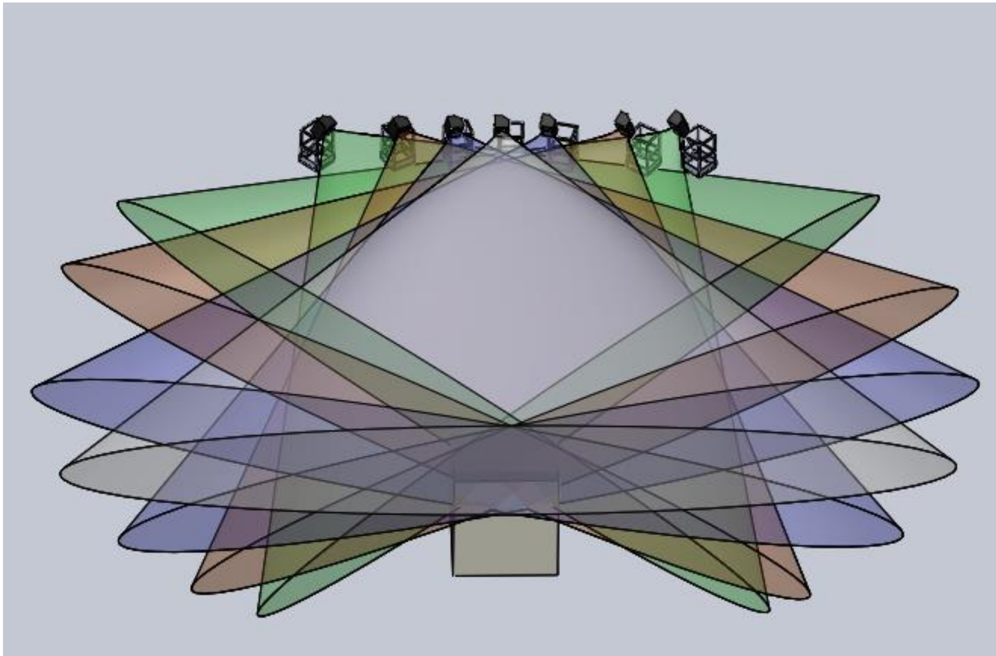


Figure 4.5: Nominal radiation angles of the speaker elevated at 30' from an elevated rear view of the test house

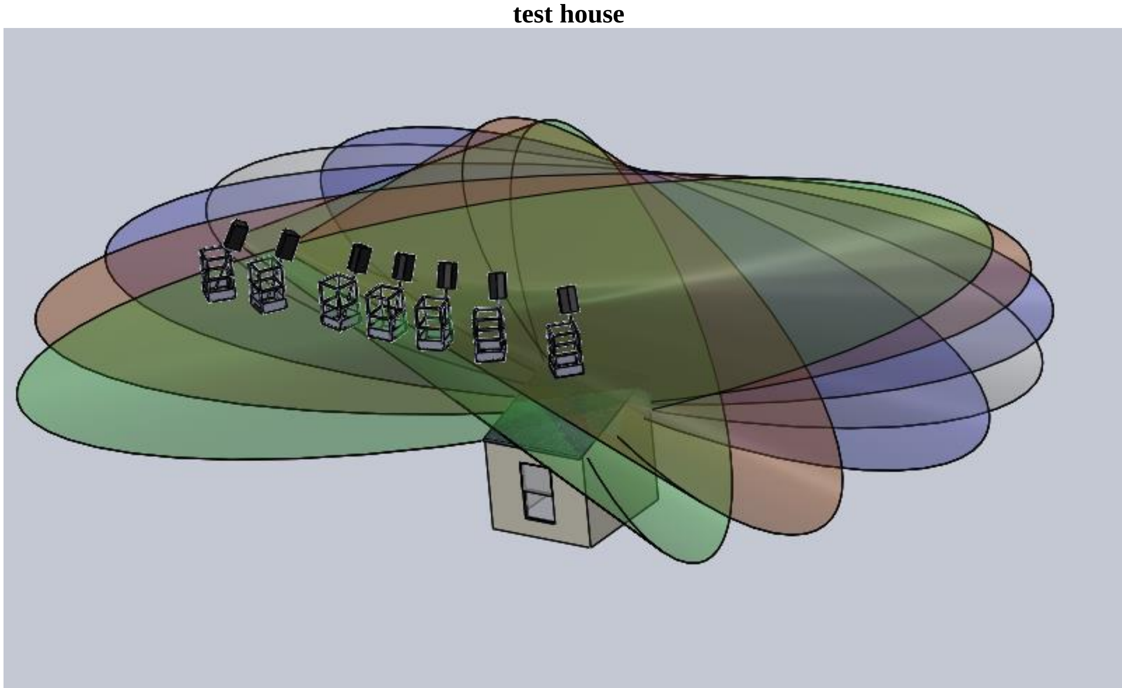


Figure 4.6: Nominal radiation angles of the speaker elevated at 30' from a front corner view

The lift locations were also used for tripod testing, so that a comparison of measured NLR values could be made across all five heights at the same source locations. The moving method was once again used since it was determined that it was the most reproducible of the methods. Figure 4.7 contains the NLR values for moving method tests taken at the lift locations with source heights of 3’5”, 7’, 15’, 20’, and 30’. Upon examination, it is clear that the tripod mounted speaker tests resulted in lower NLR values than the lift mounted speaker tests. This was expected, as Wyle collected similar results when comparing the tripod loudspeaker mount to the elevated speaker loudspeaker mount for the BTV report [20].

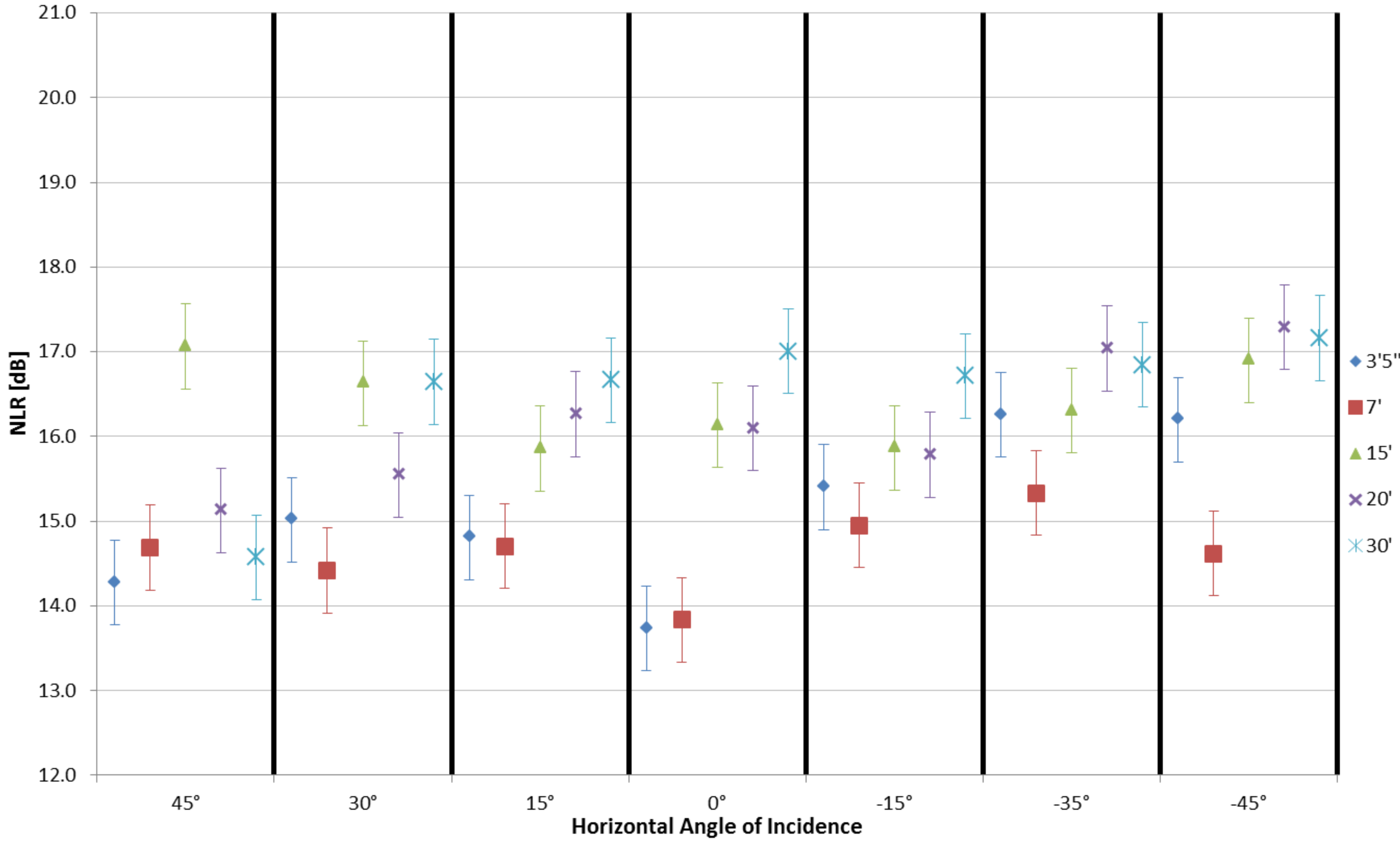


Figure 4.7: NLR values for lift locations using moving method

4.3 Window STC Rating

As discussed previously, the test house was designed such that the window is easily interchangeable allowing for testing of windows with varying acoustical performance. The two windows tested had STC ratings of 25 and 31. Ideally, the window would have been the weakest element of the test house wall; thus, the NLR of the structure should have increased when the STC rating of the window increased. Based off of theoretical calculations using the STC rating of the composite wall, there should have been about a 5 dB increase in NLR when replacing the STC 25 window with the STC 31 window. Additionally, Thomas performed a similar comparison measuring the NR with both windows and measured about a 3 dB to 5dB difference in NR values between the STC 25 and STC 31 windows [22]. However, upon looking at the differences between the tripod testing performed with both window presented in Table 4.7, it was determined that this was not the case. The mean differences between the two windows for the fixed flush, fixed near, and moving tests are 0.2 dB, 0.3, dB, and 0 dB. This means that the test house was subject to significant flanking paths in order for the wall to not have changes in NLR performance. Some flanking paths were seen near the roof, corners of the house, and window opening. The fact that the house was designed to be a modular structure, rather than a permanent construction, to allow for the greatest variation in testing most likely contributed to some of these flanking paths. Additionally, it was determined upon deconstruction of the house that there had been settling within the walls as well as damage due to the elements. The STC 25 window testing was executed first beginning in December and therefore was completed when the wall was at its peak condition, while the first STC 31 window test was not started until mid-March, thus the test house construction may have been damaged by exposure to the elements in that time span.

Table 4.7: Difference in NLR between the STC 31 and STC 25 windows the tripod mounted radial locations

Difference [dB] = STC 31 – STC 25			
Measurement	**Fixed Flush (FF)**	**Fixed Near (FN)**	**Moving (M)**
3'5'' 15 °	0.6	0.7	-1
3'5'' 30 °	1.2	1.9	-0.8
3'5'' 45 °	-0.7	-0.2	-0.7
3'5'' 60 °	0.7	2.1	0.5
3'5'' 75 °	0.1	0.2	0.1
7' 15 °	-0.3	2.2	-0.6
7' 30 °	-0.3	0.9	0.7
7' 45 °	0	-1.1	0.2
7' 60 °	0.5	-0.9	0.2
7' 75 °	0.8	-2.5	1
Max	1.2	2.2	1
Min	-0.7	-2.5	-1
Range	1.9	4.7	2
Mean	0.2	0.3	0

In addition to the comparison performed against the STC 25 window, the radial and linear locations of the NLR with the STC 31 window were examined for any possible conclusions regarding the source parameters. Figure 4.8 contains the NLR measurements for the radial locations. The slight decrease in NLR values with increasing angles of incidence is seen as a general trend when looking across all measurements, but does not remain consistent upon closer examination. While the 3’5” fixed flush and fixed near data appear to follow the trend, both have a sudden shift in increased NLR values at 60°. The moving method remains fairly constant across all angles of incident and both heights, with a range of 0.8 dB for 3'5" and 1.2 dB for 7' as was seen in the lift mounted testing. The average NLR of the moving method was once again less than those measured for the other methods, but the difference was about 0.5 dB with the STC 31 window.

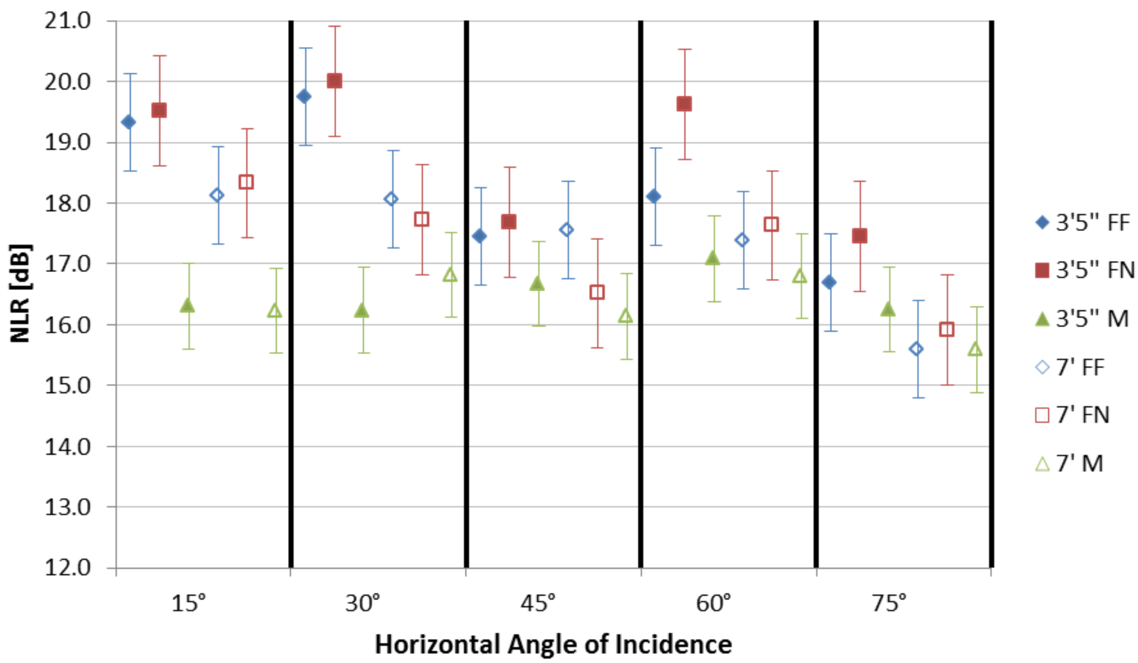


Figure 4.8: NLR values for radial locations of tripod mounted source with STC 31 window

The NLR for the STC 31 window was also examined at the linear locations as was performed with the STC 25 window NLR measurements. The comparison of the NLR values measured at linear locations to the NLR values measured at radial locations is presented in Figure 4.9. The NLR between the locations starts within 0.5 dB from each other at a 15° angle of incidence, but that difference increases to 2.3 dB at an angle of incidence of 75°. The same behavior in NLR measurements was seen between the source locations for the STC 25 window. Additionally, there was a difference of 1.0 dB between the average NLR of the radial and linear locations, which is similar to the 0.9 dB difference of the STC 25 window.

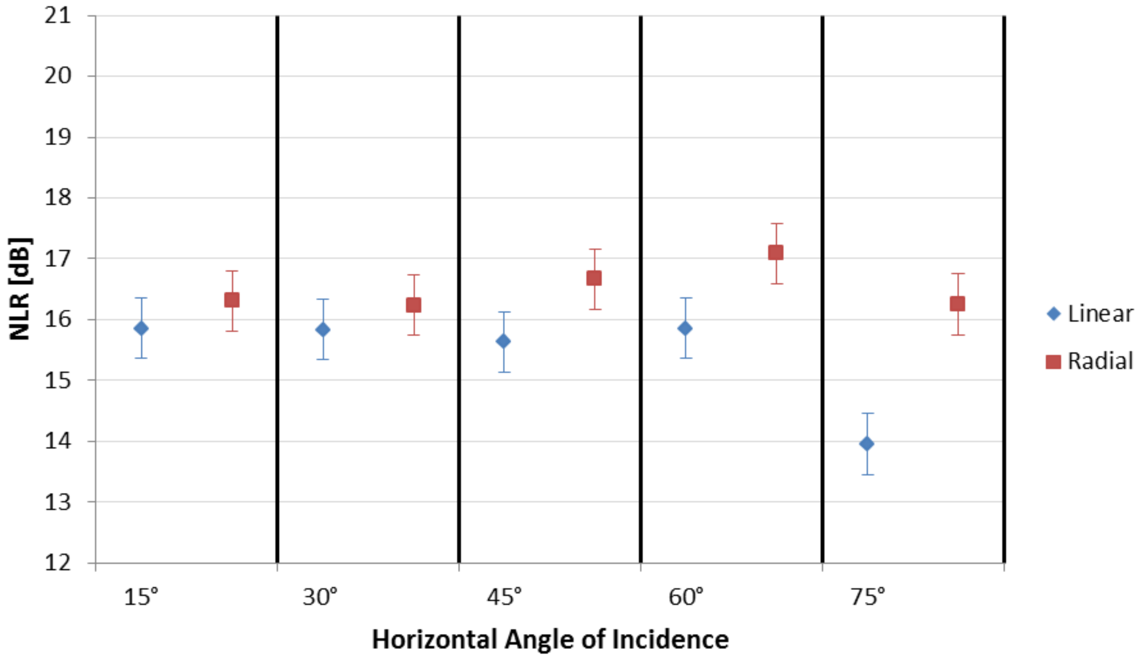


Figure 4.9: NLR values for the linear and radial locations for 3'5" source with STC 31 window and moving method

4.4 Window Condition

The other construction iteration that was completed was the window iterations, which served as a way to check that the measured results matched theoretical expectations. Although a minimal impact was noticed with the changing of the windows, an opening in the wall should have had a significant impact to the NR performance of the wall. This was confirmed in Table 4.8 for both windows by a reduction of at least 5 dB for both windows, similar to the example presented in section 1.1.

Table 4.8: NLR measurements for window conditions of each window

NLR [dB]		
Condition	**STC 25**	**STC 31**
Closed	16.5	15.6
1/2 Open	9.6	10.2
Open	8.0	8.0

4.5 Cosine Correction of NLR

In an effort to reduce the effects the angle of incidence has on NLR measurements, a cosine correction procedure was examined to determine a cosine corrected NLR (CCNLR) value. If the cosine correction works, it would be easier to perform measurements in the field as it would simplify the measurements. The CCNLR values would not be dependent on angle of incidence as is the case for NLR measurements. The CCNLR value was calculated by

$$\mathrm{CCNLR} = \mathrm{NLR} - 10 * \log\left(\cos\left(\Phi\right)\right) \text{ [dB]}, \tag{4.4}$$

where Φ is the three-dimensional angle depicted in Figure 4.10. Φ is calculated by

$$\Phi = \tan^{-1}\left(\frac{Y}{\sqrt{X^2 + H^2}}\right) \text{ [°]}. \tag{4.5}$$

Y is the source offset perpendicular to the façade, *X* is the distance from normal incidence to the sound source measured parallel to the façade, and *H* is the height of the sound source. The cosine correction should allow all of the measurements to be compared against each other regardless of angle of incidence, effectively becoming the same measurement.

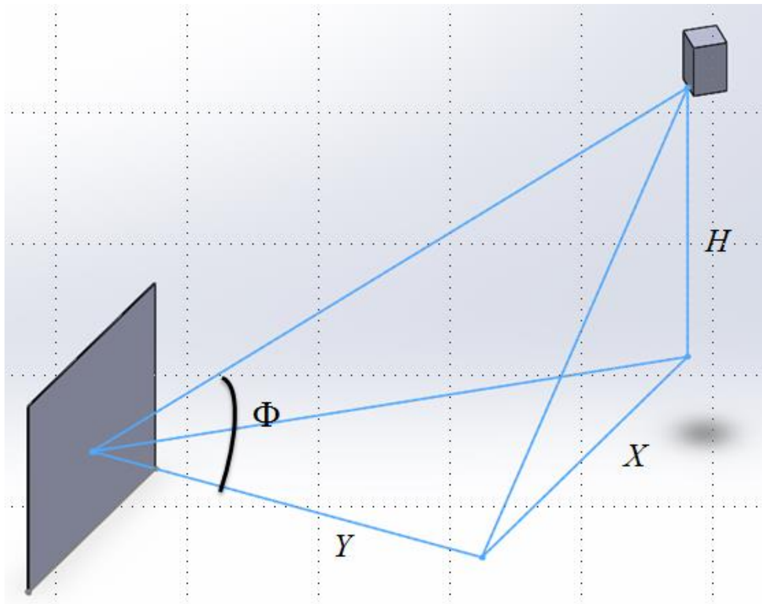


Figure 4.10: Diagram of three-dimensional angle of incidence, Φ

CCNLR values were calculated for the lift mounted testing and the tripod mounted radial location testing for both the STC 25 and STC 31 windows. The figures presented earlier in the report for these tests are presented again below for convenience in comparing the measured NLR values to the calculated CCNLR values. Figure 4.11 and Figure 4.12 contain the NLR and CCNLR values for the lift mounted speaker testing. There are no real noticeable improvements between the NLR and CCNLR values for the lift mounted testing. In some instances, the data for a specific angle or test will have a smaller range, but in others the range increases. An example of this is seen with the moving method tests, the correction reduces the spread at 45° but increases it at 15° and 0°. The tripod mounted testing of the radial locations for the STC 25 window are pictured with the NLR values in Figure 4.13 and CCNLR in Figure 4.14. The final comparison of NLR and CCNLR is made with the STC 31 window radial locations in Figure 4.15 and Figure 4.16 respectively. The results of the cosine correction are more discernible on the tripod mounted speaker data. As the angle of incidence increases, the value of CCNLR increases. The increase is significant, as it is near 5 dB for the 75° measurements. Especially with the tripod mounted testing, the NLR values remained fairly constant regardless of angle of incidence; thus, the NLR values at higher angles of incidence increased after applying the correction. Therefore, it was determined that the cosine correction should not be used in the analysis of NLR measurements.

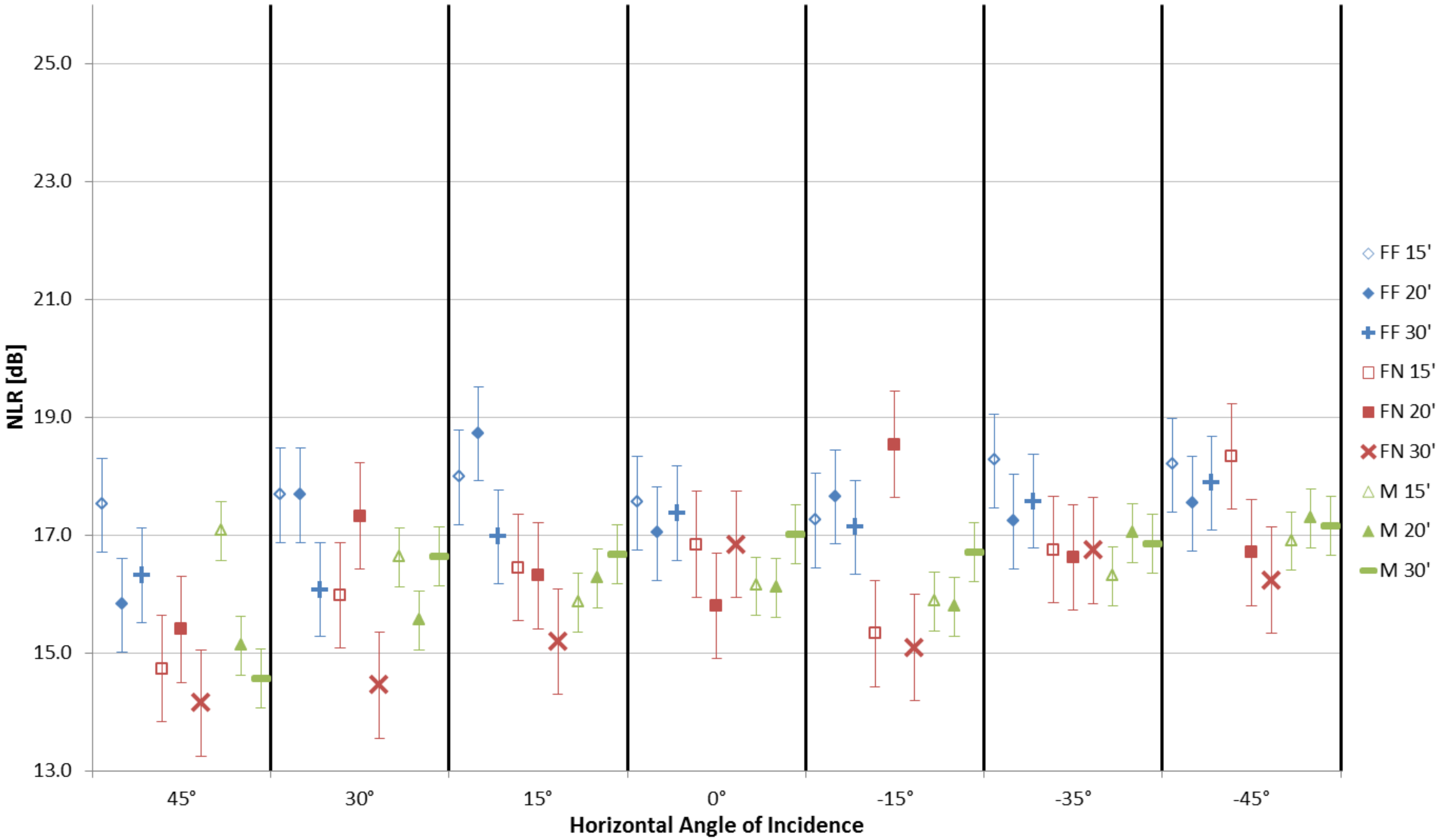


Figure 4.11: NLR values of the lift mounted speaker measurements

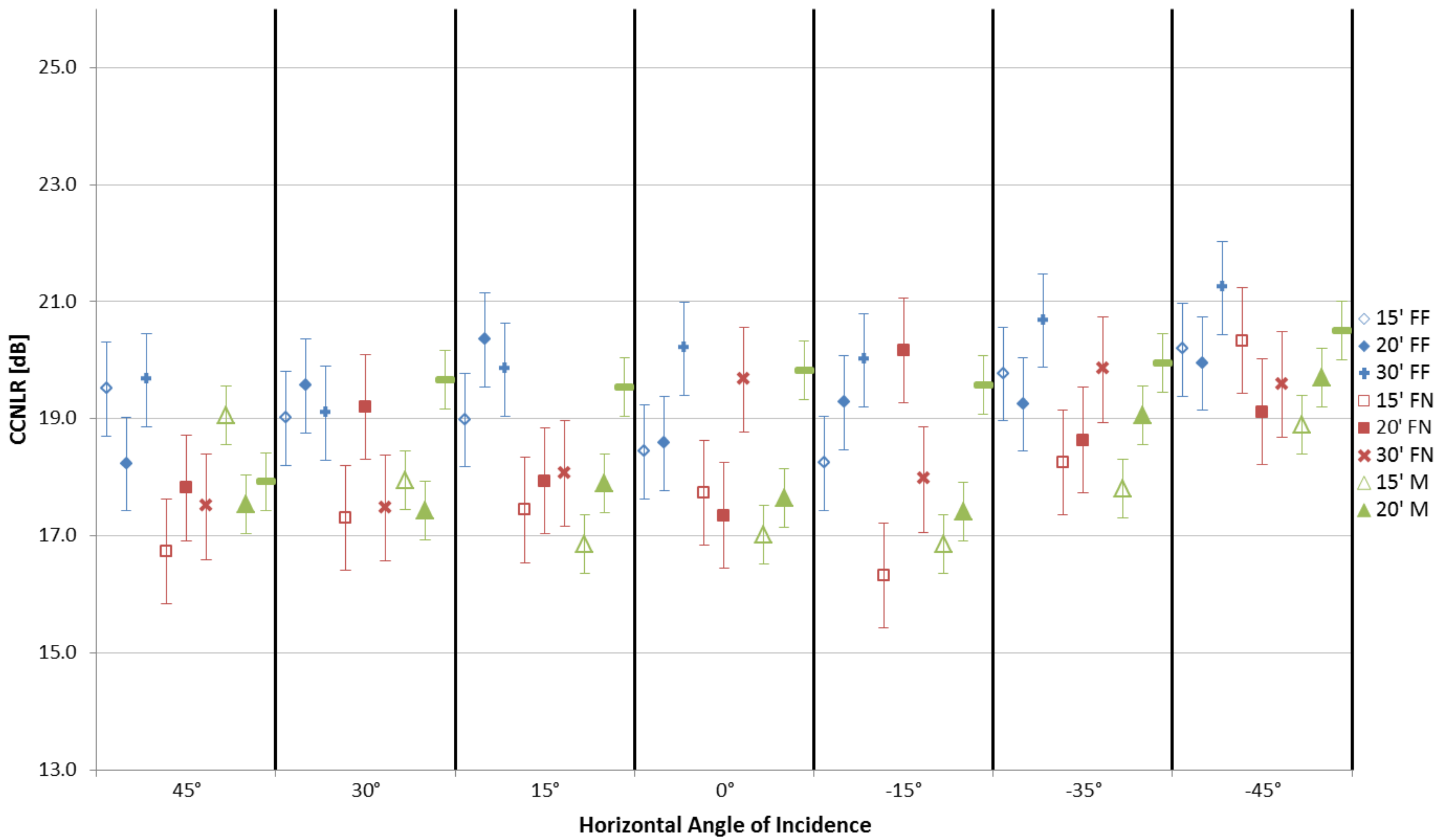


Figure 4.12: CCNLR values of the lift mounted speaker measurements

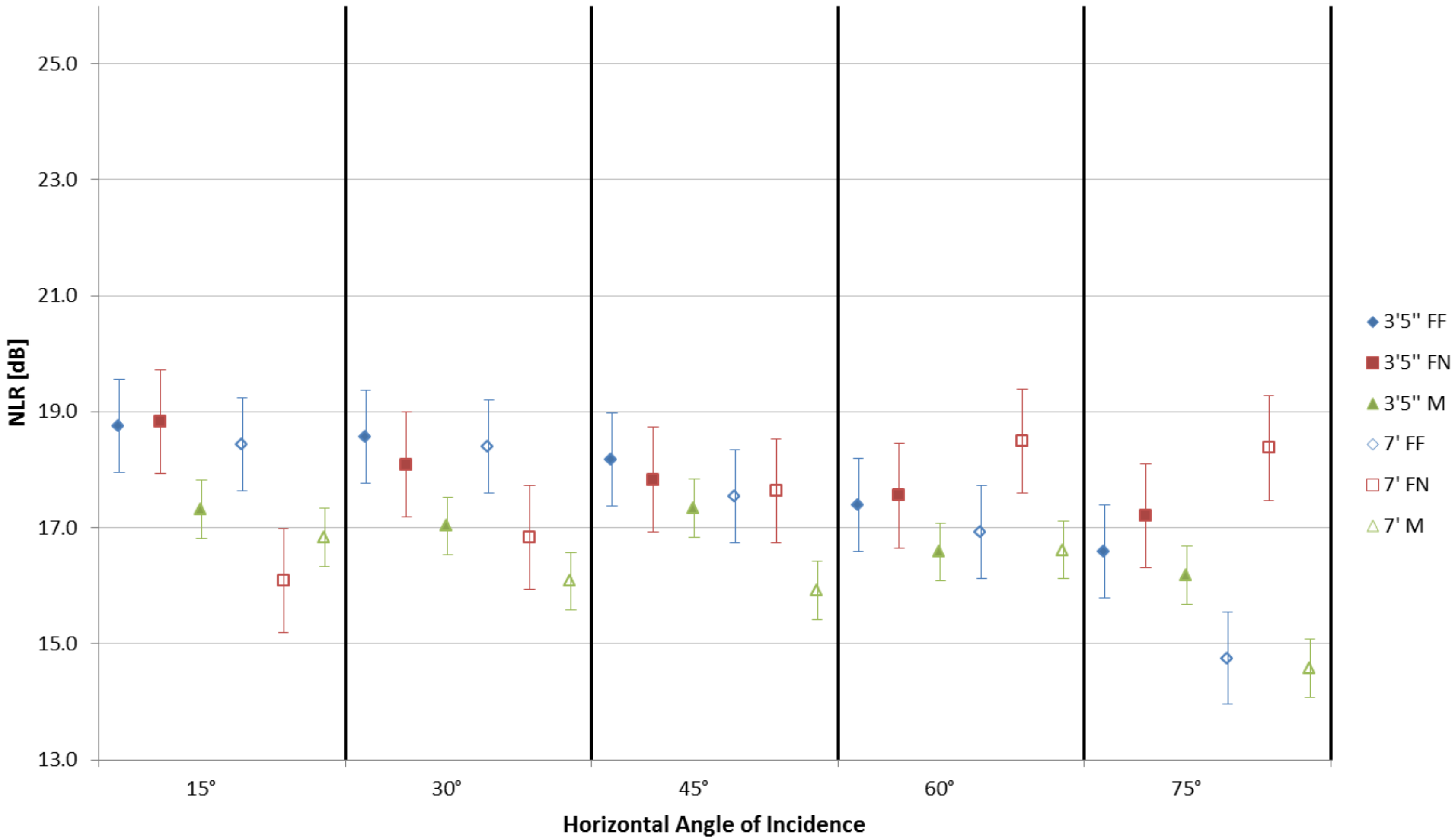


Figure 4.13: NLR values for radial locations of tripod mounted source with STC 25 window

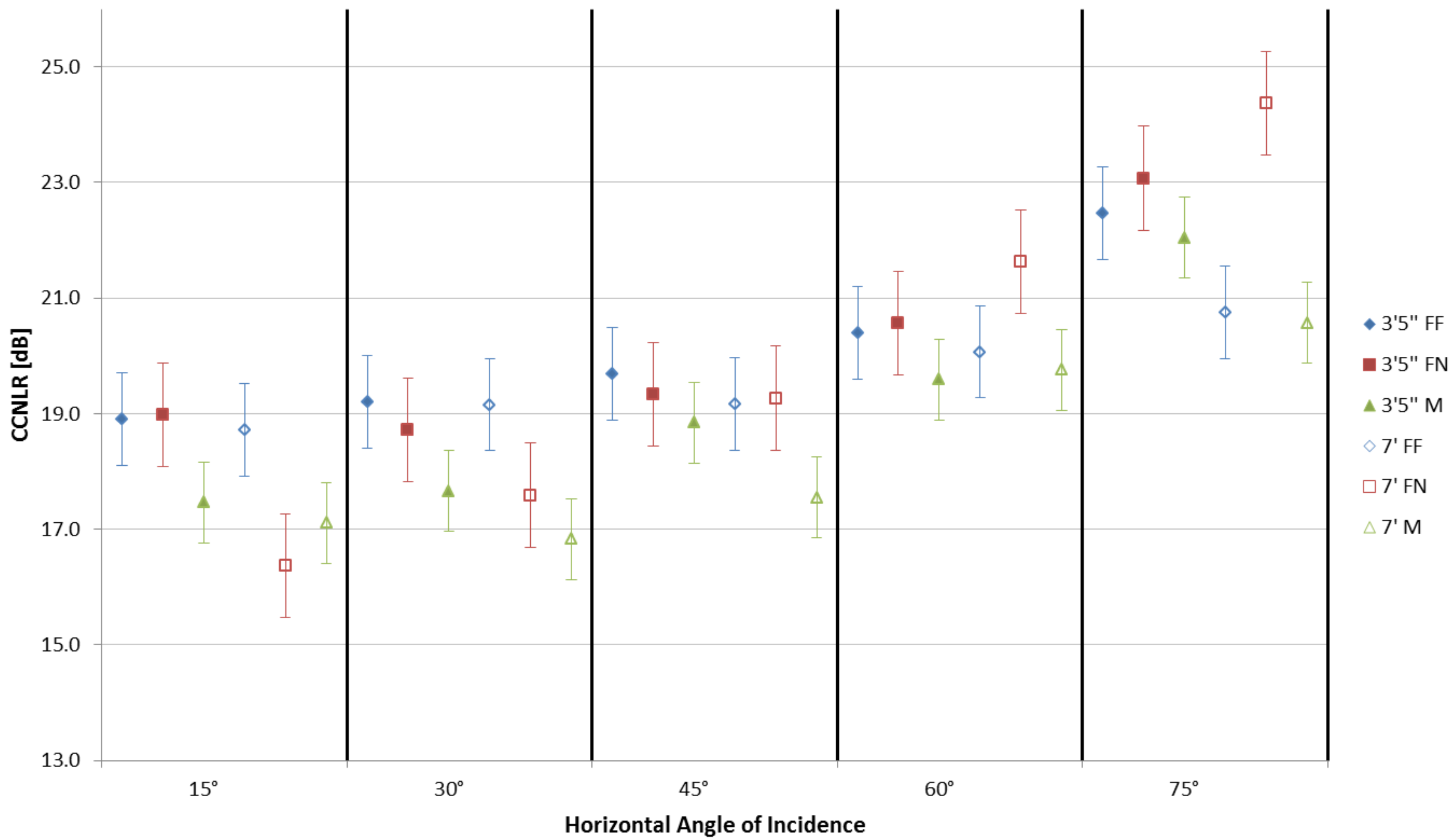


Figure 4.14: CCNLR values for radial locations of tripod mounted source with STC 25 window

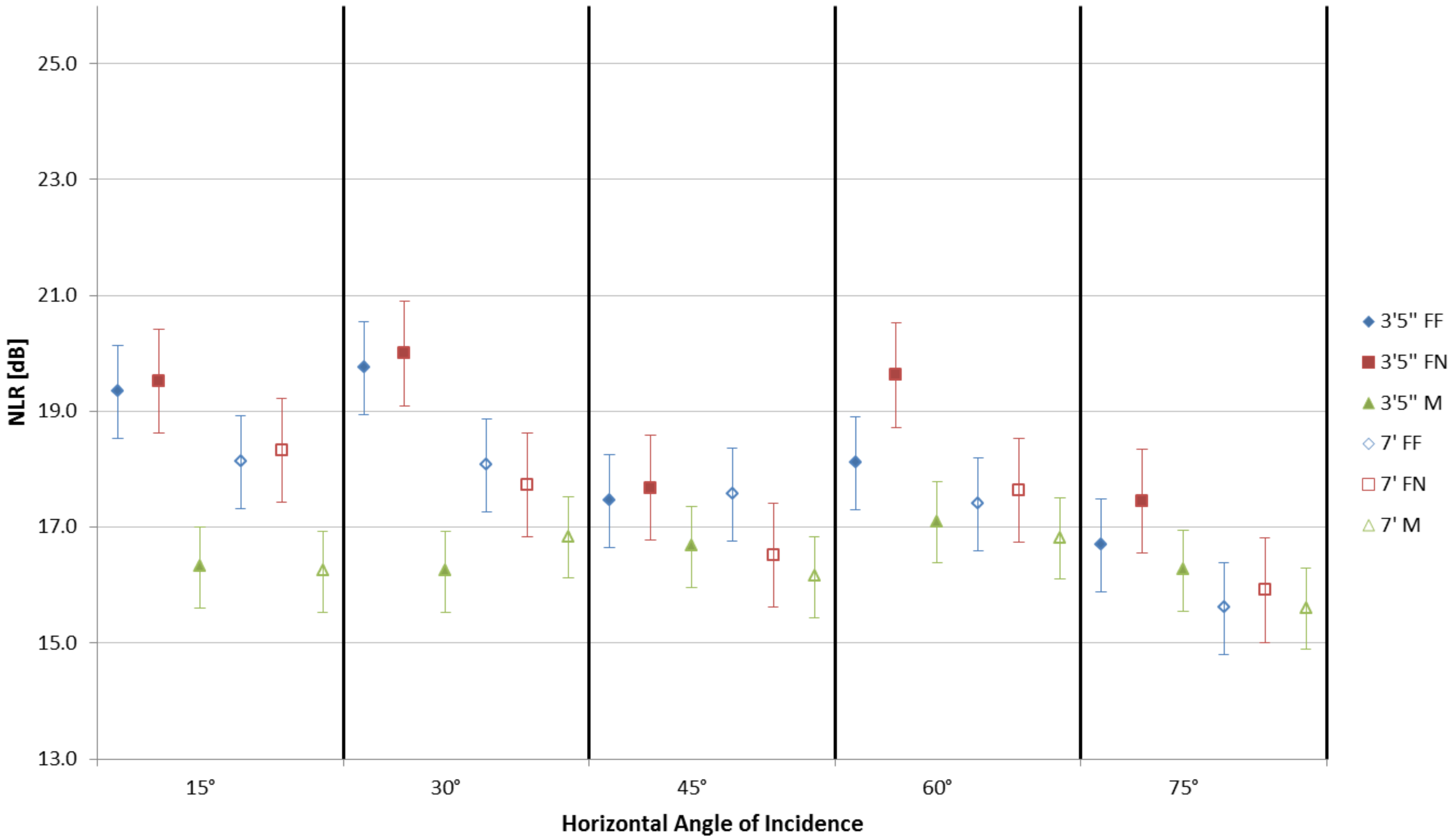


Figure 4.15:NLR values for radial locations of tripod mounted source with STC 31 window

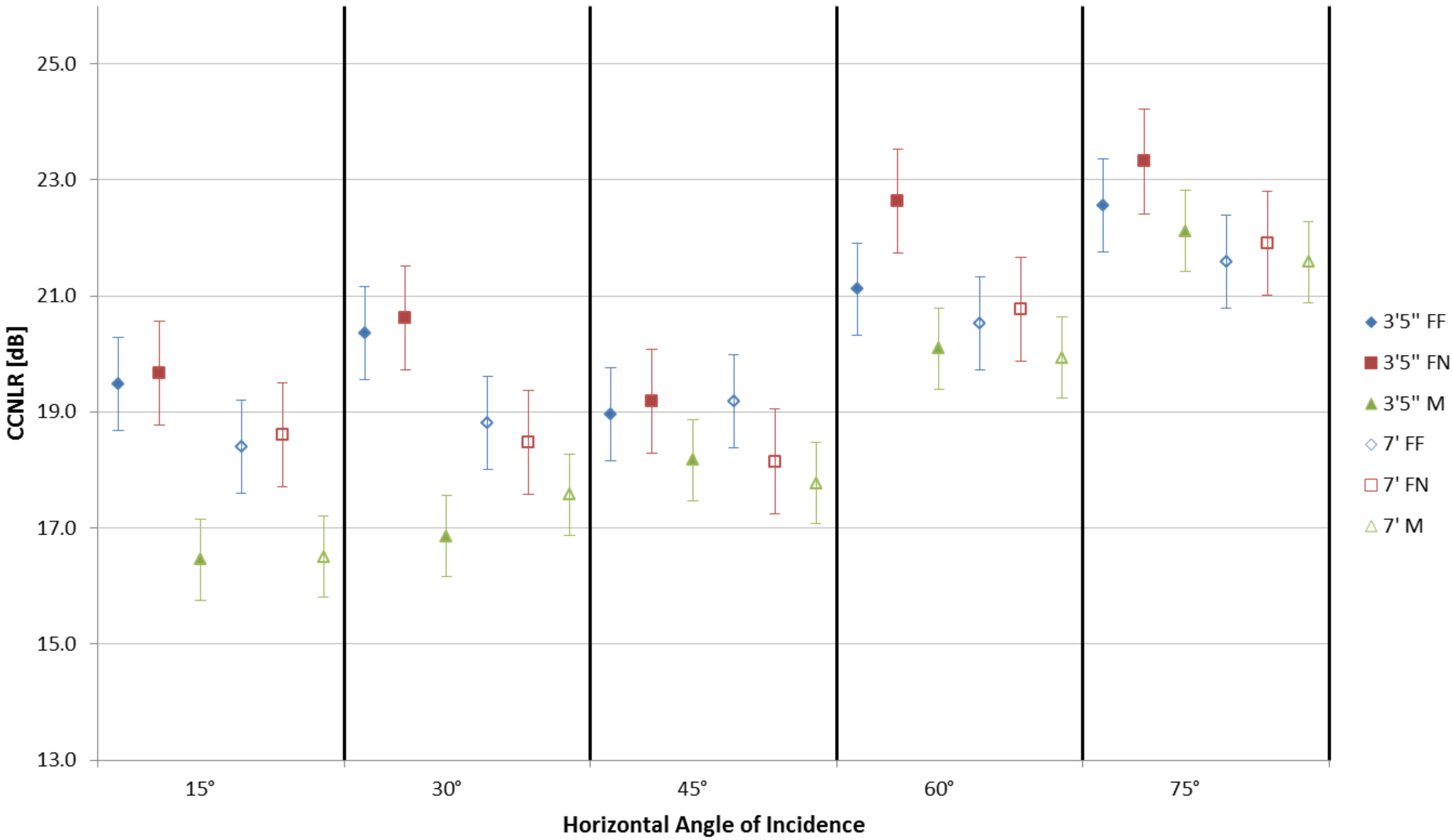


Figure 4.16: CCNLR values for radial locations of tripod mounted source with STC 31 window

4.6 Application of Foam Insulation to Flanking Paths

Application of expanding foam was used to treat some flanking paths after seeing the minimal effect that changing the window had on the NLR measurements. Great Stuff ™ insulating foam sealant was used to treat possible flanking paths present in both the interior and exterior of the house. The foam was applied to any gaps or cracks found present in construction. The NLR was measured at the lift locations with the tripod mounted speaker using the moving method. The results of these measurements before and after application of the foam are presented in Table 4.9. There was a significant increase in the acoustic performance of the wall with an average increase in NLR of 3.4 dB after applying the foam, but there was still no clear angular dependency seen in Figure 4.17.

Table 4.9: NLR values before and after application of foam

NLR [dB]			
	Pre-Foam	**Post-Foam**	**Difference**
3'4'' 45°	14.3	18.8	4.5
3'4'' 30°	15.0	17.9	2.9
3'4'' 15°	14.8	17.4	2.6
3'4'' 0°	13.7	16.9	3.2
3'4'' -15°	15.4	18.7	3.3
3'4'' -35°	16.3	19.3	3.1
3'4'' -45°	16.2	18.2	2.0
7' 45°	14.7	18.1	3.4
7' 30°	14.4	18.1	3.7
7' 15°	14.7	17.7	3.0
7' 0°	13.8	17.8	3.9
7' -15°	15.0	18.0	3.1
7' -35°	15.3	19.0	3.6
7' -45°	14.6	19.0	4.4
		Mean Difference =	3.4

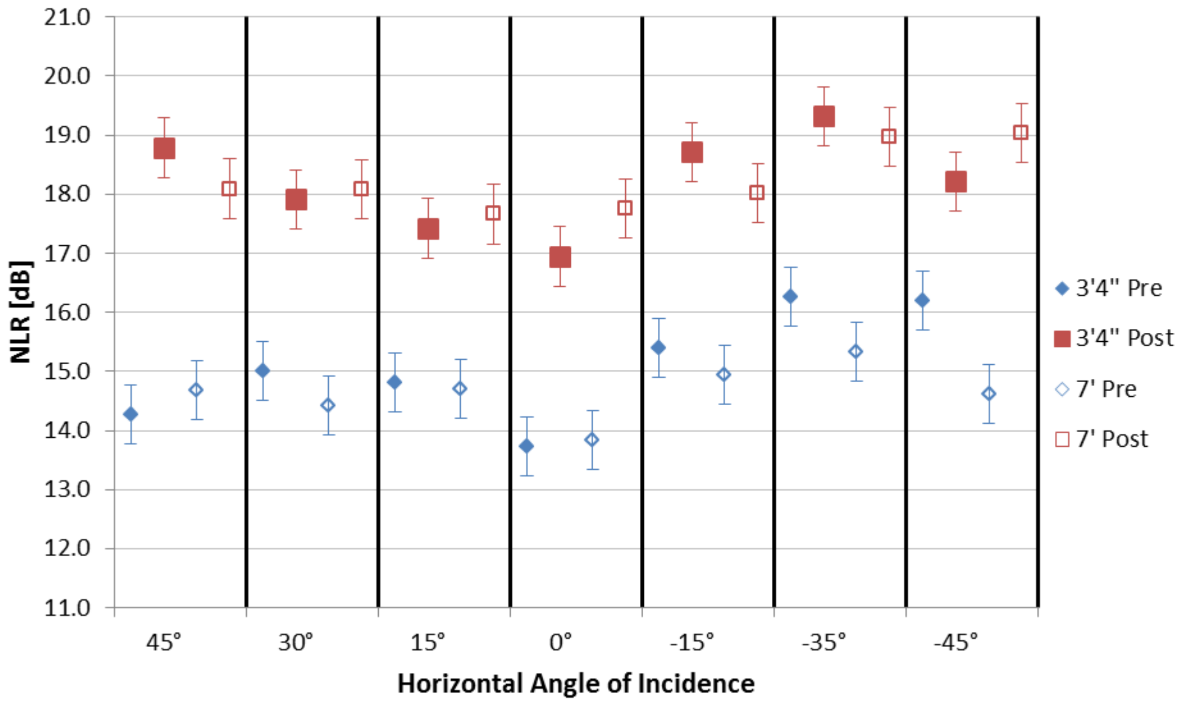


Figure 4.17: NLR values measured before and after foam application

CHAPTER 5

CONCLUSIONS

Sound insulation programs are an important measure in place to mitigate the effect of aircraft noise on communities surrounding airports. Eligibility for the program is outlined in Program Guidance Letter 12-09 requiring an exterior Day-Night Average Sound Level (DNL) of at least 65 dBA and an interior DNL of at least 45 dBA [35]. Noise Level Reduction (NLR) is an important metric for these programs in the United States as the interior DNL is often calculated by subtracting the measured NLR of a building from the exterior DNL.

The NLR of a building is measured using either aircraft flyovers as the sound source or using an artificial noise source such as a loudspeaker. The accuracy of NLR measurements is important since they may determine the eligibility of a residence for sound insulation programs, but there are a number of key challenges in measuring the NLR of a building. One challenge is the inherent difference between the two types of tests. Aircraft flyovers are a time-varying line source while a loudspeaker is a static point source. Booms or lifts may be used to elevate the loudspeaker to better approximate the angles of incidence from an aircraft flyover. However, a loudspeaker is a more diffuse sound source than an aircraft flyover as it is a directional source. Since the angles of incidence of an aircraft flyover vary over time, the exposure of a building and sound level also vary over the course of a flyover. The difference in NLR values measured with both tests is not known, but consultants at Landrum & Brown measured a mean difference of 2.4 dB in their measurements performed near the Burlington International Airport [20].

The purpose of this study was to further evaluate NLR measurements using the loudspeaker test. The overall goal is to provide a resource on different parameters of the loudspeaker test to the aircraft noise industry. The specific parameters evaluated over the course of the research are horizontal angle of incidence, vertical angle of incidence (source height), repeatability, reproducibility, source offset, and microphone placement. A test house was constructed with materials and methods of a mixed humid climate to provide a site for all of the NLR measurements.

The statistics of each of the measurement methods was identified through repeatability and reproducibility testing. The reproducibility test determined that the fixed flush method was the most repeatable, that is provided the most precise results when implementing identical tests. The repeatability 95% confidence interval (CI) for the fixed flush method was calculated to be ±0.3 dB. However, it was determined that the moving method provided the most reproducible results with a 95% confidence interval (CI) of 0.5 dB. Reproducibility is a better metric of precision as it is the precision for a procedure rather than a specific test; thus, it was concluded that the moving method was the most precise test.

The variation in NLR measurements caused by the source location was measured with a loudspeaker mounted on a tripod and man lift with an STC 25 window. With the loudspeaker mounted on a tripod and altered on the radial locations at an angle of incidence of 75°, the NLR values decreased likely due to the side façade affecting the measurement of the front façade since the speaker was approaching grazing. The locations of the tripod were also varied linearly such that the source variations were on the same plane at an equal offset from the façade. These locations resulted in a measured

NLR an average of 1 dB less than the average NLR measured for the radial locations. This was expected since the speaker was nearly forty feet away from the center of the façade for the loudspeaker at the 75° angle of incidence linear location. The average moving test across all angles of incidence was 1 dB less than the average measured by the fixed near and fixed flush methods.

The testing performed with the speaker mounted on the man lift was used to evaluate the vertical angle of incidence as well as the symmetry of the measurements, but no clear angular dependency was observed. It was determined that the measurements were not symmetric for the test house, as the NLR values were not consistently similar across either side of normal incidence. The lack of symmetry in NLR measurements is likely due to flanking paths present in the construction. Once again, the moving method measured NLR values about 1 dB less than the fixed flush method. When comparing the measurements between the tripod and lift testing, it was determined that the tripod mounted testing resulted in NLR values that were less than the lift mounted testing.

Testing was also completed with two construction iterations: the acoustic performance of the window and window condition. In addition to the testing performed with the STC 25 window, NLR of the test house with an STC 31 window was also measured. The changing of the window offered minimum changes in NLR. The minimal changes were likely due to flanking paths present in the walls of the test house. Application of expanding foam to minimize flanking paths resulted in an average increase of 3.4 dB NLR; however, there was still no clear angular dependency after applying the foam.

Overall, changes in NLR were observed across all of the measurements, but the measurements did not exhibit consistent angular dependency. It is suggested to implement the moving method for NLR measurements with the loudspeaker test as it was the most reproducible. Future testing should examine the correction factor for the moving method, as the average NLR for the radial locations test with both windows and the lift mounted tests was at least 1 dB less than the fixed flush method. Additionally, correction factors should be considered when measuring NLR with a tripod mounted speaker rather than an elevated source or when altering the source locations linearly rather than radially. A set procedure to measure NLR with a loudspeaker would also be beneficial in reducing variations allowed currently.

Lastly, comparisons between the loudspeaker and aircraft flyover method should be examined further, including the overall accuracy of each method. Currently, the measurements do not appear to be similar due to the characteristics of the sources; a fixed point source and a time varying line source are used as equivalent methods of testing a spectrum dependent method. The artificial noise source method may be better suited to perform measurements to determine the acoustic performance of a building before and after modifications, as is stated as the primary goal of these measurements for the FAA in ASTM E966-10 [21]. In other words, the artificial noise method may be better suited for comparative rather than absolute measurements.

5.1 Future Work

Future work should include an attempt to create a set procedure for measuring NLR with the loudspeaker test or aircraft flyover test. For the loudspeaker test, the procedure may include source parameters, microphone locations, and calculation procedures. If the procedure includes both a tripod mounted speaker or elevated speaker, a correction factor should be examined to have a more accurate comparison. The calculation of NLR from NR values should be stated including the frequencies to be reported and qualifications for the aircraft spectra to be used in calculations. A procedure addressing these parameters should increase the precision of NLR measurements by reducing the variation of testing in the field.

Additionally, the effect of the construction quality on NLR measurements should be examined. Future testing could be done to see how improvements to the acoustic performance of a building affect NLR measurements and values. Measurements using the loudspeaker test with this type of study will help to identify the capabilities of the loudspeaker test at measuring NLR before and after modifications. Additionally, the study could also be used as a resource, more specifically in the building construction community, at showing the effect that quality construction has on acoustic performance.

APPENDIX A

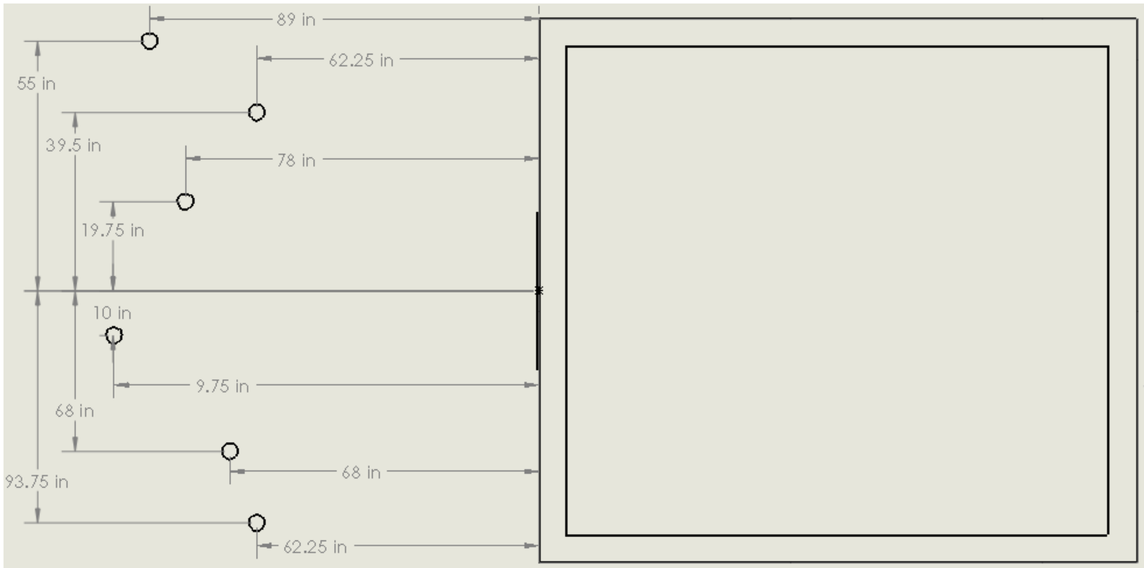


Figure A.1: Drawing of exterior fixed near measurement locations

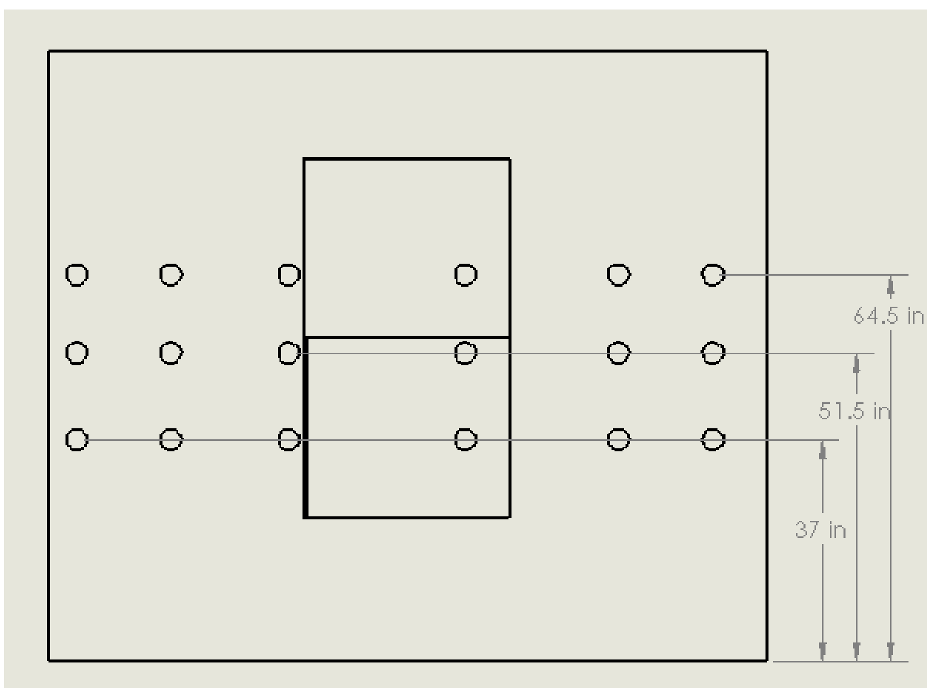


Figure A.2: Drawing of heights of fixed measurement locations

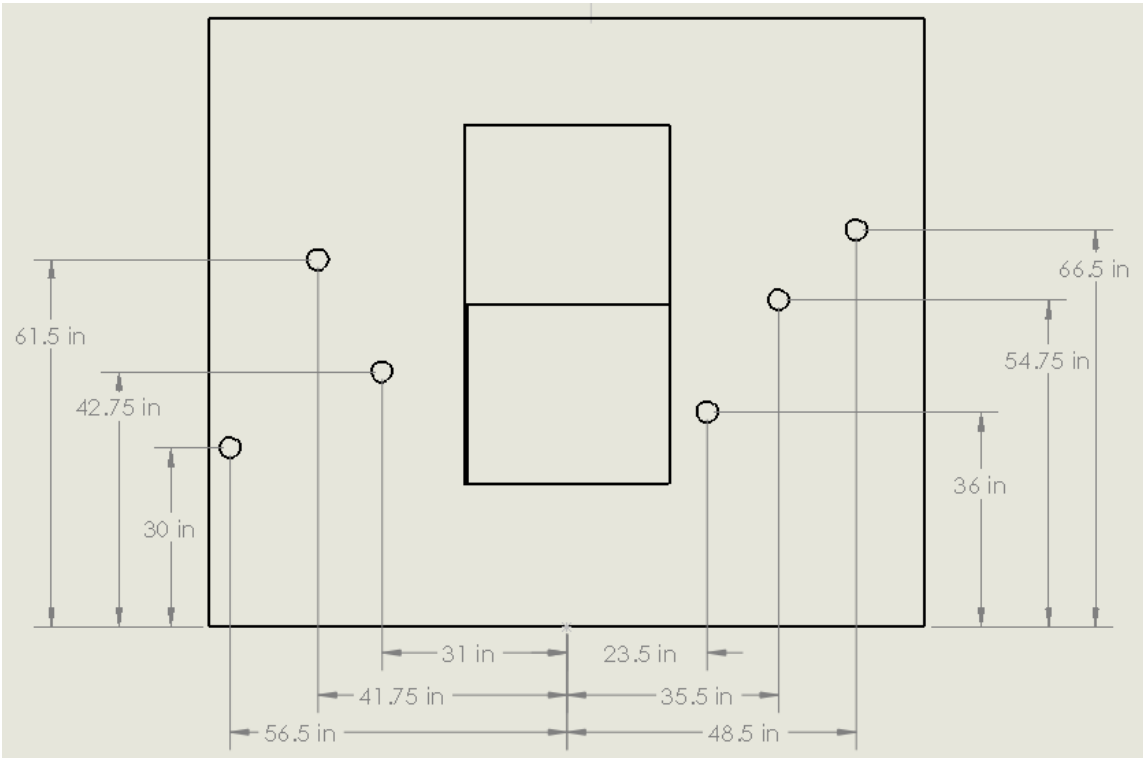


Figure A.3: Drawing of exterior fixed flush measurement locations

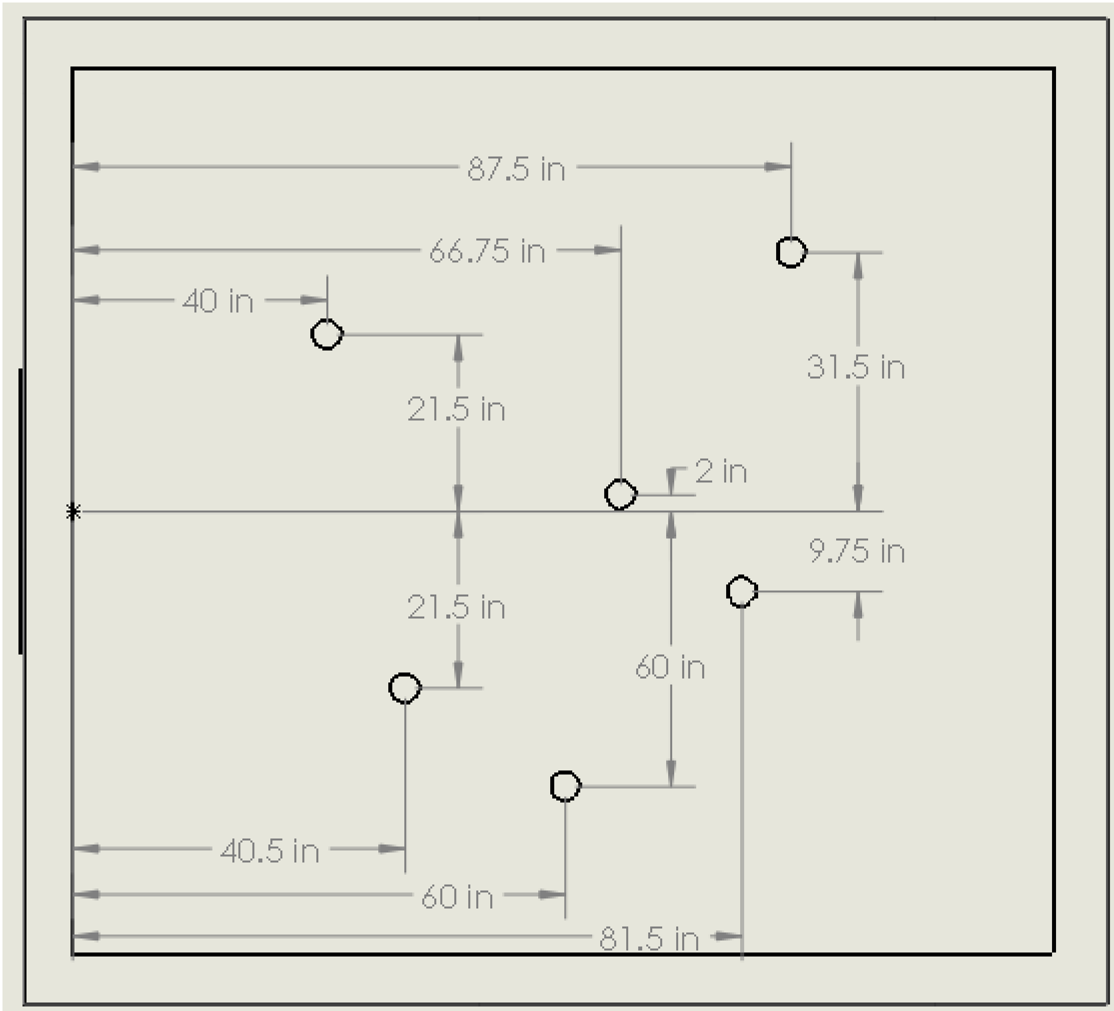


Figure A.4: Drawing of interior fixed measurement locations

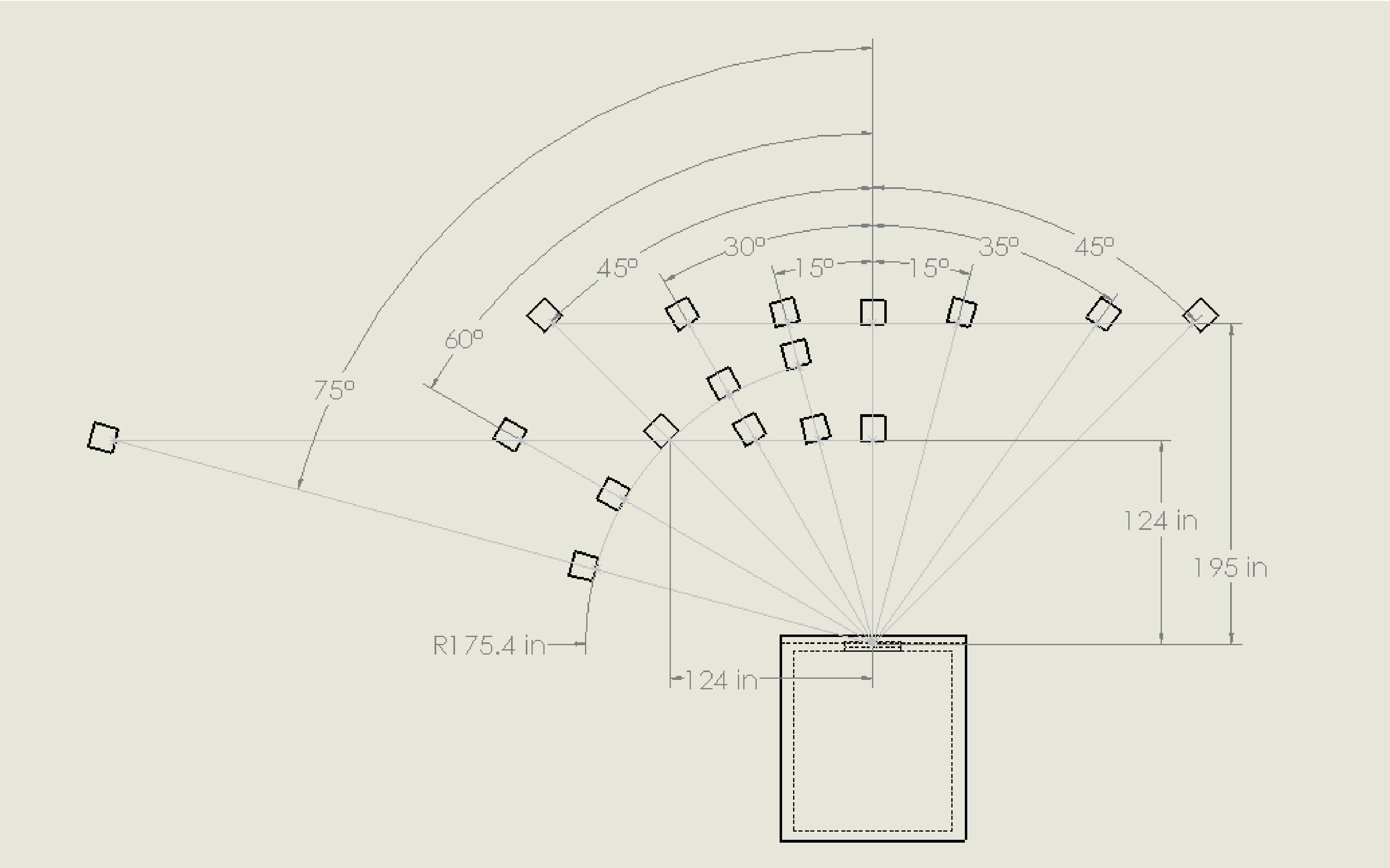


Figure A.5: Drawing of sound source locations

APPENDIX B

Table B.1: Summary of iterations and NLR measured for each

#	Measurement Type	Window STC	Window Condition	Angle of Incidence	Source Height	NLR [dB]	Comments
1	Fixed Flush	25	Closed	45°	3.4'	17.9	Repeatability
2	Fixed Flush	25	Closed	45°	3.4'	18.3	
3	Fixed Flush	25	Closed	45°	3.4'	18.4	
4	Fixed Flush	25	Closed	45°	3.4'	18.4	
5	Fixed Flush	25	Closed	45°	3.4'	18.2	
6	Fixed Flush	25	Closed	45°	3.4'	16.2	Reproducibility
7	Fixed Flush	25	Closed	45°	3.4'	16.4	
8	Fixed Flush	25	Closed	45°	3.4'	17.0	
9	Fixed Flush	25	Closed	45°	3.4'	16.6	
10	Fixed Flush	25	Closed	45°	3.4'	16.2	
11	Moving	25	Closed	45°	3.4'	16.3	Repeatability
12	Moving	25	Closed	45°	3.4'	15.7	
13	Moving	25	Closed	45°	3.4'	16.8	
14	Moving	25	Closed	45°	3.4'	16.2	
15	Moving	25	Closed	45°	3.4'	16.4	
16	Moving	25	Closed	45°	3.4'	16.3	Reproducibility
17	Moving	25	Closed	45°	3.4'	15.7	
18	Moving	25	Closed	45°	3.4'	16.8	
19	Moving	25	Closed	45°	3.4'	16.2	
20	Moving	25	Closed	45°	3.4'	16.4	
21	Fixed Near	25	Closed	45°	3.4'	17.3	Repeatability
22	Fixed Near	25	Closed	45°	3.4'	17.5	
23	Fixed Near	25	Closed	45°	3.4'	17.6	
24	Fixed Near	25	Closed	45°	3.4'	17.6	
25	Fixed Near	25	Closed	45°	3.4'	17.3	
26	Fixed Near	25	Closed	45°	3.4'	16.8	Reproducibility
27	Fixed Near	25	Closed	45°	3.4'	17.8	
28	Fixed Near	25	Closed	45°	3.4'	16.1	
29	Fixed Near	25	Closed	45°	3.4'	17.7	
30	Fixed Near	25	Closed	45°	3.4'	18.2	
31	Fixed Near	25	Closed	15°	3.4'	18.8	Radius
32	Fixed Near	25	Closed	30°	3.4'	18.1	
33	Fixed Near	25	Closed	45°	3.4'	17.8	
34	Fixed Near	25	Closed	60°	3.4'	17.6	

Table B.1 (cont.): Summary of iterations and NLR measured for each

#	Measurement Type	Window STC	Window Condition	Angle of Incidence	Source Height	NLR [dB]	Comments
35	Fixed Near	25	Closed	75°	3.4'	17.2	
36	Fixed Flush	25	Closed	15°	3.4'	18.8	Radius
37	Fixed Flush	25	Closed	30°	3.4'	18.6	
38	Fixed Flush	25	Closed	45°	3.4'	18.2	
39	Fixed Flush	25	Closed	60°	3.4'	17.4	
40	Fixed Flush	25	Closed	75°	3.4'	16.6	
41	Moving	25	Closed	15°	3.4'	17.3	Radius
42	Moving	25	Closed	30°	3.4'	17.0	
43	Moving	25	Closed	45°	3.4'	17.3	
44	Moving	25	Closed	60°	3.4'	16.6	
45	Moving	25	Closed	75°	3.4'	16.2	
46	Fixed Near	25	Closed	15°	7'	16.1	Radius
47	Fixed Near	25	Closed	30°	7'	16.8	
48	Fixed Near	25	Closed	45°	7'	17.6	
49	Fixed Near	25	Closed	60°	7'	18.5	
50	Fixed Near	25	Closed	75°	7'	18.4	
51	Fixed Flush	25	Closed	15°	7'	18.4	Radius
52	Fixed Flush	25	Closed	30°	7'	18.4	
53	Fixed Flush	25	Closed	45°	7'	17.5	
54	Fixed Flush	25	Closed	60°	7'	16.9	
55	Fixed Flush	25	Closed	75°	7'	14.8	
56	Moving	25	Closed	15°	7'	16.8	Radius
57	Moving	25	Closed	30°	7'	16.1	
58	Moving	25	Closed	45°	7'	15.9	
59	Moving	25	Closed	60°	7'	16.6	
60	Moving	25	Closed	75°	7'	14.6	
61	Moving	25	Half Open	45°	3.4'	9.6	Window Iterations
62	Moving	25	Open	45°	3.4'	8.0	
63	Moving	25	Closed	0°	3.4'	16.6	Equal Offset
64	Moving	25	Closed	15°	3.4'	16.7	
65	Moving	25	Closed	30°	3.4'	16.9	
66	Moving	25	Closed	45°	3.4'	16.5	
67	Moving	25	Closed	60°	3.4'	15.5	
68	Moving	25	Closed	75°	3.4'	13.4	
69	Fixed Near	31	Closed	15°	3.4'	19.5	Radius
70	Fixed Near	31	Closed	30°	3.4'	20.0	
71	Fixed Near	31	Closed	45°	3.4'	17.7	

Table B.1 (cont.): Summary of iterations and NLR measured for each

#	Measurement Type	Window STC	Window Condition	Angle of Incidence	Source Height	NLR [dB]	Comments
72	Fixed Near	31	Closed	60°	3.4'	19.6	Radius
73	Fixed Near	31	Closed	75°	3.4'	17.5	
74	Fixed Flush	31	Closed	15°	3.4'	19.3	Radius
75	Fixed Flush	31	Closed	30°	3.4'	19.7	
76	Fixed Flush	31	Closed	45°	3.4'	17.5	
77	Fixed Flush	31	Closed	60°	3.4'	18.1	
78	Fixed Flush	31	Closed	75°	3.4'	16.7	
79	Moving	31	Closed	15°	3.4'	16.3	Radius
80	Moving	31	Closed	30°	3.4'	16.2	
81	Moving	31	Closed	45°	3.4'	16.7	
82	Moving	31	Closed	60°	3.4'	17.1	
83	Moving	31	Closed	75°	3.4'	16.3	
84	Fixed Near	31	Closed	15°	7'	18.3	Radius
85	Fixed Near	31	Closed	30°	7'	17.7	
86	Fixed Near	31	Closed	45°	7'	16.5	
87	Fixed Near	31	Closed	60°	7'	17.6	
88	Fixed Near	31	Closed	75°	7'	15.9	
89	Fixed Flush	31	Closed	15°	7'	18.1	Radius
90	Fixed Flush	31	Closed	30°	7'	18.1	
91	Fixed Flush	31	Closed	45°	7'	17.6	
92	Fixed Flush	31	Closed	60°	7'	17.4	
93	Fixed Flush	31	Closed	75°	7'	15.6	
94	Moving	31	Closed	15°	7'	16.2	Radius
95	Moving	31	Closed	30°	7'	16.8	
96	Moving	31	Closed	45°	7'	16.1	
97	Moving	31	Closed	60°	7'	16.8	
98	Moving	31	Closed	75°	7'	15.6	
99	Moving	31	Half Open	45°	3.4'	10.2	Window Iterations
100	Moving	31	Open	45°	3.4'	8.0	
101	Moving	31	Closed	0°	3.4'	16.1	Equal Offset
102	Moving	31	Closed	15°	3.4'	15.9	
103	Moving	31	Closed	30°	3.4'	15.8	
104	Moving	31	Closed	45°	3.4'	15.6	
105	Moving	31	Closed	60°	3.4'	15.9	
106	Moving	31	Closed	75°	3.4'	13.9	
107	Fixed Near	25	Closed	45°	15'	14.7	
108	Fixed Flush	25	Closed	45°	15'	17.5	

Table B.1 (cont.): Summary of iterations and NLR measured for each

#	Measurement Type	Window STC	Window Condition	Angle of Incidence	Source Height	NLR [dB]	Comments
109	Moving	25	Closed	45°	15'	17.1	
110	Fixed Near	25	Closed	30°	15'	16.0	
111	Fixed Flush	25	Closed	30°	15'	17.7	
112	Moving	25	Closed	30°	15'	16.6	
113	Fixed Near	25	Closed	15°	15'	16.5	
114	Fixed Flush	25	Closed	15°	15'	18.0	
115	Moving	25	Closed	15°	15'	15.9	
116	Fixed Near	25	Closed	0°	15'	16.8	
117	Fixed Flush	25	Closed	0°	15'	17.5	
118	Moving	25	Closed	0°	15'	16.1	
119	Fixed Near	25	Closed	-15°	15'	15.3	
120	Fixed Flush	25	Closed	-15°	15'	17.2	
121	Moving	25	Closed	-15°	15'	15.9	
122	Fixed Near	25	Closed	-35°	15'	16.8	
123	Fixed Flush	25	Closed	-35°	15'	18.3	
124	Moving	25	Closed	-35°	15'	16.3	
125	Fixed Near	25	Closed	-45°	15'	18.3	
126	Fixed Flush	25	Closed	-45°	15'	18.2	
127	Moving	25	Closed	-45°	15'	16.9	
128	Fixed Near	25	Closed	45°	20'	15.4	
129	Fixed Flush	25	Closed	45°	20'	15.8	
130	Moving	25	Closed	45°	20'	15.1	
131	Fixed Near	25	Closed	30°	20'	17.3	
132	Fixed Flush	25	Closed	30°	20'	17.7	
133	Moving	25	Closed	30°	20'	15.5	
134	Fixed Near	25	Closed	15°	20'	16.3	
135	Fixed Flush	25	Closed	15°	20'	18.7	
136	Moving	25	Closed	15°	20'	16.3	
137	Fixed Near	25	Closed	0°	20'	15.8	
138	Fixed Flush	25	Closed	0°	20'	17.0	
139	Moving	25	Closed	0°	20'	16.1	
140	Fixed Near	25	Closed	-15°	20'	18.5	
141	Fixed Flush	25	Closed	-15°	20'	17.6	
142	Moving	25	Closed	-15°	20'	15.8	
143	Fixed Near	25	Closed	-35°	20'	16.6	
144	Fixed Flush	25	Closed	-35°	20'	17.2	
145	Moving	25	Closed	-35°	20'	17.0	

Table B.1 (cont.): Summary of iterations and NLR measured for each

#	Measurement Type	Window STC	Window Condition	Angle of Incidence	Source Height	NLR [dB]	Comments
146	Fixed Near	25	Closed	-45°	20'	16.7	
147	Fixed Flush	25	Closed	-45°	20'	17.5	
148	Moving	25	Closed	-45°	20'	17.3	
152	Fixed Near	25	Closed	45°	30'	14.1	
153	Fixed Flush	25	Closed	45°	30'	16.3	
154	Moving	25	Closed	45°	30'	14.6	
155	Fixed Near	25	Closed	30°	30'	14.5	
156	Fixed Flush	25	Closed	30°	30'	16.1	
157	Moving	25	Closed	30°	30'	16.6	
158	Fixed Near	25	Closed	15°	30'	15.2	
159	Fixed Flush	25	Closed	15°	30'	17.0	
160	Moving	25	Closed	15°	30'	16.7	
161	Fixed Near	25	Closed	0°	30'	16.8	
162	Fixed Flush	25	Closed	0°	30'	17.4	
163	Moving	25	Closed	0°	30'	17.0	
164	Fixed Near	25	Closed	-15°	30'	15.1	
165	Fixed Flush	25	Closed	-15°	30'	17.1	
166	Moving	25	Closed	-15°	30'	16.7	
167	Fixed Near	25	Closed	-35°	30'	16.7	
168	Fixed Flush	25	Closed	-35°	30'	17.6	
149	Moving	25	Closed	-35°	30'	16.8	
150	Fixed Near	25	Closed	-45°	30'	16.2	
151	Fixed Flush	25	Closed	-45°	30'	17.9	
169	Moving	25	Closed	-45°	30'	17.2	
170	Moving	25	Closed	45°	3.4'	14.3	Lift Location
171	Moving	25	Closed	30°	3.4'	15.0	
172	Moving	25	Closed	15°	3.4'	14.8	
173	Moving	25	Closed	0°	3.4'	13.7	
174	Moving	25	Closed	-15°	3.4'	15.4	
175	Moving	25	Closed	-35°	3.4'	16.3	
176	Moving	25	Closed	-45°	3.4'	16.2	
177	Moving	25	Closed	45°	7'	14.7	Lift Location
178	Moving	25	Closed	30°	7'	14.4	
179	Moving	25	Closed	15°	7'	14.7	
180	Moving	25	Closed	0°	7'	13.8	
181	Moving	25	Closed	-15°	7'	15.0	
182	Moving	25	Closed	-35°	7'	15.3	

Table B.1 (cont.): Summary of iterations and NLR measured for each

#	Measurement Type	Window STC	Window Condition	Angle of Incidence	Source Height	NLR [dB]	Comments
183	Moving	25	Closed	-45°	7'	14.6	Lift Location
184	Moving	25	Closed	45°	3.4'	18.8	Lift Location with Expanding Foam
185	Moving	25	Closed	30°	3.4'	17.9	
186	Moving	25	Closed	15°	3.4'	17.4	
187	Moving	25	Closed	0°	3.4'	16.9	
188	Moving	25	Closed	-15°	3.4'	18.7	
189	Moving	25	Closed	-35°	3.4'	19.3	
190	Moving	25	Closed	-45°	3.4'	18.2	
191	Moving	25	Closed	45°	7'	18.1	Lift Location with Expanding Foam
192	Moving	25	Closed	30°	7'	18.1	
193	Moving	25	Closed	15°	7'	17.7	
194	Moving	25	Closed	0°	7'	17.8	
195	Moving	25	Closed	-15°	7'	18.0	
196	Moving	25	Closed	-35°	7'	19.0	
197	Moving	25	Closed	-45°	7'	19.0	

REFERENCES

[1] Wyle, "Updating and Supplementing the Day-Night Average Sound Level (DNL)," Department of Transportation, 2011.

[2] Wolfgang Babisch, Danny Houthuijs, Göran Pershagen, Ennio Cadum, Klea Katsouyanni, Manolis Velonakis, *et al.*, "Annoyance due to aircraft noise has increased over the years—results of the HYENA study," *Environment international*, vol. 35, pp. 1169-1176, 2009.

[3] Geoffrey D Gosling, "2001: An Airspace Odyssey SUMMARY PROCEEDINGS OF THE 2001 AIRPORT NOISE SYMPOSIUM AND AIRPORT AIR QUALITY SYMPOSIUM," *Institute of Transportation Studies*, 2001.

[4] FAA US DOT, "Guidelines for Sound Insulation of Residences Exposed to Aircraft Operations," 1992.

[5] *AIP Eligibility and Justification Requirements for Noise Insulation Documents*, D. o. Transportation, 2012.

[6] James P. Cowan, *Handbook of Environmental Acoustics*. New York, NY: Van Nostrand Reinhold, 1994.

[7] Pacific Northwest National Laboratory, "Guide to Determining Climate Regions by County," 2015.

[8] U.S. Department of Energy, "Introduction to building systems performance: Houses that work II," *Building America*, 2004.

[9] Nathan Firesheets, "Modeling the transmission loss of typical home constructions exposed to aircraft noise," 2012.

[10] GAO, "Results from a Survey of the Nation's 50 Busiest Commercial Service Airports," *Aviation and the Environment*, p. 78, 2000.

[11] Washington Navy Yard, "Guidelines for Sound Insulation of Residences Exposed to Aircraft Operations," ed: Department of the Navy Naval Facilities Engineering Command, Washington DC, 2005.

[12] FAA US DOT, "Study - The Feasibility, Practicability and Cost of the Soundproofing of Schools, Hospitals, and Public Health Facilities Located near Airports," ED 148 029, 1977.

[13] Trans Systems Corporation and Wyle Laboratories, "Study of Soundproofing Public Buildings near Airports," Federal Aviation Administration Office of Environmental Quality DOT-FAA-AEQ-77-9, 1977.

[14] Michael K Payne, Rita A Smith, Deborah Murphy Lagos, Jack Freytag, Mark Culverson, Jean Lesicka*, et al.*, *Guidelines for Airport Sound Insulation Programs*, 2013.

[15] FAA, "Airport Improvement Program Handbook," U. DOT, Ed., ed, 2014.

[16] Randall F Barron, *Industrial noise control and acoustics*: CRC Press, 2002.

[17] M David Egan, *Architectural acoustics*: McGraw-Hill Custom Publishing, 1988.

[18] *Noise Level Reduction Design and Construction Standards*, Ammendment to International Building Code Appendix F, 2008.

[19] ASTM International, "Standard Classification for Rating Outdoor-Indoor Sound Attenuation," in *ASTM E1332-10a*, ed. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. United States, 2010.

[20] Inc. Landrum & Brown, "Study of Noise Level Reduction (NLR) Variation," FAA, 2013.

[21] ASTM International, "Standard guide for field measurements of airborne sound attenuation of building facades and façade elements," in *ASTM E966-10*, ed. 100 Barr Harbor Drive, P.O. Box C-700 West Conshohocken, Pennsylvania 19428-2959, 2011.

[22] Ashwin Paul Thomas, "Simulated and Laboratory Models of Aircraft Sound Transmission," Master of Science, Mechanical Engineering, Georgia Institute of Technology, 2014.

[23] Airport Cooperative Research Program (ACRP), "Guidelines for Airport Sound Insulation Program," FAA, 2013.

[24] Hua He, "Aviation noise transmission indoors-Overview of FAA research and assessment of future research needs," in *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 2014, pp. 263-270.

[25] ASTM International, "Standard Test Method for Laboratory Measurement of Noise Reduction of Sound-Isolating Enclosures," in *ASTM E596-96*, ed. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, 2009.

[26] ASTM International, "Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements," in *ASTM E90-09*, ed. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, 2009.

[27] ASTM International, "Classification for Rating Sound Insulation," in *ASTM E413-10*, ed. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, 2010.

[28] JA Birta, JS Bradley, and T Estabrooks, "IBANA-Calc User's Manual," 2001.

[29] ASTM International, "Standard Guide for Applting Environmental Noise Measurement Methods and Criteria," in *ASTM E1686-10*, ed. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, 2015.

[30] PEQ ESA, and CDM, "FAR PART 150 STUDY: Noise Exposure Maps Report," Hartsfield-Jackson Atlanta International Airport, March 21, 2007, 2007.

[31] Paul Schomer Vincent Mestre, Stanford Fidell, and Bernard Berry, "Technical Support for Day/Night Average Sound Level (DNL) Replacement Metric Research," Department of Transportation, 2011.

[32] Inc American National Standard Institute, "Specifications for Intereating-Averaging Sound Level Meters," in *ANSI S1.43-1997*, ed, 1997.

[33] International Electrotechnical Commission, "Electroacoustics - Sound Level Meters - Part 1: Specifications," in *IEC 61672-1:2013*, ed, 2013.

[34] JS Bradley and WT Chu, "Errors when using facade measurements of incident aircraft noise," 2002.

[35] FAA US DOT, "Eligibility and Justification Requirements for Rev. November 7,2012 Noise Insulation Projects," 2012.